Dynamics of the Southern Hemisphere Spiral Jet

LINDSEY N. WILLIAMS, SUKYOUNG LEE, AND SEOK-WOO SON

Department of Meteorology, The Pennsylvania State University, University Park, Pennsylvania

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ABSTRACT

The formation of the Southern Hemisphere spiral jet is investigated using observations over a 40-yr period. It is found that between late March and early April, the upper-tropospheric westerly jet in the Southern Hemisphere undergoes a transition from an annular structure in midlatitudes to a spiral structure that extends from 20° to 55°S. The transition to the spiral structure is initiated by the formation of a subtropical jet, localized in the central Pacific. The inception of the jet spiral is completed with the formation of a band of northwest-to-southeast-oriented zonal winds, which is connected to both the subtropical and the polar-front jets. This band, referred to as the tilting branch, arises from momentum flux convergence associated with breaking Rossby waves. As such, the direction of the wave breaking determines the direction of the jet spiral; an anticyclonic wave breaking, associated with equatorward wave dispersion, establishes a jet spiral that turns cyclonically toward the pole.

This formation mechanism of the jet spiral is supported by a set of calculations with an idealized numerical model. These model calculations indicate that the jet spiral is obtained only if the model’s localized subtropical jet is sufficiently strong, and if the latitude of the polar-front jet is sufficiently higher than that of the subtropical jet. The calculations also indicate that the spiral jet is a transient solution, implying that the lack of spiral structure during the austral winter may be caused by the zonal wind field reaching a new statistically steady state.

1. Introduction

One peculiar feature in the atmosphere, which does not seem to have received much attention, is the fact that large-scale westerly jets, at times, take on a spiral form. An example of the spiral jet structure is shown in Fig. 1, which displays the 275-hPa Southern Hemisphere (SH) zonal wind field, corresponding approximately to a 40-yr calendar mean of 27 April. A more precise description of the data and averaging procedure will be given in section 2. Starting from the southern tip of Madagascar, the westerly maxima gradually spirals poleward, clockwise, ending at about midway between New Zealand and Antarctica. The jet climatologies in Bals-Elsholz et al. (2001) show that the Northern Hemisphere (NH) westerlies also exhibit a spiral structure (see their Figs. 1 and 6) except for the summer season. For reasons that are not apparent, as shown in Fig. 1, it is also during this time period, from autumn to spring, that the SH jet takes on a spiral form. During the SH winter and spring, the SH jet is better characterized as a localized split jet (Chen et al. 1996; Bals-Elsholz et al. 2001).

The spiral-jet structure is not only observed in the atmosphere, but also in the shallow-water model used by Cho and Polvani (1996). In the presence of rotation, and without asymmetric stationary forcing, their model results show spontaneously generated vorticity bands that exhibit a spiral structure. It may well be that the key mechanism behind the spiral bands in this shallow-water model and that in the atmosphere differs from each other. However, it is interesting to observe that in both the atmosphere and the model, the direction of the spiral is cyclonic, that is, in the same direction as the underlying solid-body rotation. In the NH (SH), the jet spirals counterclockwise (clockwise) toward the pole.

The goal of the study is to investigate mechanisms for the spiral-jet formation in the atmosphere. The questions to be focused on are: how the spiral initially forms, why it turns cyclonically, and whether the state of the spiral jet is a steady-state solution. The last question arises from the fact that while the spiral bands appear to be robust in the shallow water model of Cho and
Polvani (1996), in the SH, they are apparent only during the SH autumn. Since the SH summer jet is close to being annular, to study the spiral formation process, we choose to examine the circulation transition from the SH summer to the SH autumn. The findings from these observations will be tested with a set of idealized numerical model experiments.

Section 2 describes data and analysis procedures. The observed spiral jet formation will be presented in section 3. Results from the numerical model will be presented in section 4. The conclusion follows in section 5.

2. Data analysis

This study uses daily National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data for January 1958 through December 1997. Forty-year composites of the zonal wind, meridional wind, and eddy streamfunction at 275 hPa are used to investigate how the spiral jet structure forms. Because of the inhomogeneous quality of the reanalysis data during this 40-yr period, calculations were also performed using only the last twenty years of data, from January 1978 to December 1997. The results are extremely consistent with those presented here, although they are not shown for brevity.

The calendar day mean of the 40-yr period shows that the subtropical jet (STJ) gains significant strength, and a spiral structure forms, on approximately 27 April. However, at any given year, it is unlikely that the formation occurs on the same calendar day. To take into account this interannual variability, instead of using the calendar mean, we adopt the following composite procedure. For each of the 40 individual years, the 275-hPa zonal wind field, between ten days prior to and ten days after 27 April, is correlated with the 40-yr calendar mean zonal wind field for 27 April. Again, 27 April is used because on approximately this day, the spiral jet becomes a distinct feature. The domain for this pattern correlation is from 120° to 62°W and from 23° to 55°S. This region is indicated in Fig. 2. For each year, within this 40-yr time period, the day at which the pattern correlation is highest is designated as the lag-0 day.

Composites of dynamic fields are then constructed with lag-0 day as the time reference. Figure 2 shows that the resulting composite wind field is overall very similar to that of the calendar mean. The main difference between the two fields seems to be the smoother and more robust spiral in the lag-0 day composite.

To examine if the spiral jet manifests itself every year, correlations are performed between the zonal wind pattern for each year at the lag 0 day and the zonal wind composite pattern. Two sets of correlations are performed using the tilting branch region and the entire SH. The average correlation coefficient for the tilting branch region is 0.8719, with the highest value being 0.9501 in 1964 and the lowest value being 0.8262 in 1972. For the SH as a whole, the average correlation coefficient is 0.8097, with the highest value being 0.8676.
in 1963 and the lowest value being 0.7563 in 1982. These consistently high correlation values, especially for the tilting branch region, indicate that the spiral pattern seen in Fig. 2 is very similar to that seen each year, and therefore support that the spiral formation is an annual event.

a. Zonal momentum budget

The zonal momentum equation is used to find which terms serve as the major contributor to the temporal change in the zonal wind field during the spiral jet formation. All variables are divided into high- and low-frequency components. The high-frequency components are obtained by applying a ten-day high-pass digital filter. The low-frequency components are then calculated by subtracting the high-frequency component from the total, unfiltered variable. The seasonal cycle is retained in the low-frequency component because the spiral is a seasonal feature and therefore eliminating the seasonal cycle would result in removing the feature being studied. With the above decomposition, the zonal-momentum equation can be written as

\[
\frac{\partial u_H}{\partial t} + \frac{\partial u_L}{\partial t} = -\frac{u_H}{a \cos \phi} \frac{\partial u_H}{\partial \lambda} - \frac{u_L}{a \cos \phi} \frac{\partial u_L}{\partial \lambda} - \frac{u_L}{a \cos \phi} \frac{\partial u_H}{\partial \lambda} - \frac{u_H}{a \cos \phi} \frac{\partial u_L}{\partial \lambda} - \frac{v_H}{a} \frac{\partial u_H}{\partial \phi} - \frac{v_L}{a} \frac{\partial u_L}{\partial \phi} - \frac{v_H}{a} \frac{\partial u_L}{\partial \phi} - \frac{v_L}{a} \frac{\partial u_H}{\partial \phi} - \frac{v_L}{a} \frac{\partial u_H}{\partial \phi} + \frac{RT}{g} \left( \frac{f' \omega_H}{a} + \frac{f' \omega_L}{a} \right) + F_x,
\]

where \( \Phi \) is the geopotential, \( a \) is the radius of the earth, \( f = 2 \Omega \sin \phi \), \( f' = 2 \Omega \cos \phi \), and \( F_x \) is friction. The approximation \( \omega \approx -\frac{\partial p}{\partial t} \) is also used. The subscripts \( H \) and \( L \) indicate high- and low-frequency components. Because the reanalysis data is produced using a spectral model, the Andes Mountains and Antarctica create artificial ripples due to Gibb’s phenomenon. This has a most adverse effect on the pressure gradient force, greatly hampering the balancing of the budget. This problem is overcome by subtracting the 40-yr annual-mean climatology for each of the budget terms. For example, the first term on the right-hand side of (1) becomes

\[
\left( \frac{u_H}{a \cos \phi} \frac{\partial u_H}{\partial \lambda} \right) = \frac{u_H}{a \cos \phi} \frac{\partial u_H}{\partial \lambda} - \frac{u_H}{a \cos \phi} \frac{\partial u_H}{\partial \lambda}.
\]

The same process is applied to each term in (1).

b. One-point correlation maps

To analyze the wave propagation characteristics associated with the jets, for each year, a perturbation streamfunction is calculated by removing the zonal mean. Using the lag-0 day as a reference, time-lagged one-point correlation maps are produced by taking each grid point in the SH as a base point. This base point is then correlated with every other grid point in the SH. To identify synoptic-scale wave packets, the perturbation field is also decomposed into high- and low-pass components.

3. Zonal wind variability

a. Synopsis of the zonal wind evolution

During the early austral summer, the polar-front jet (PFJ) is the single, dominant jet located between 35° and 55°S, and forms a nearly annular structure (Fig. 3a). The maximum westerly wind speeds are approximately 35 m s\(^{-1}\) and stretch across the southern Atlantic and Indian Oceans, with weaker 20–30 m s\(^{-1}\) winds over the southern Pacific. By late austral summer, a new maximum located over the southeastern Pacific begins to form at approximately 30°S (not shown). It slowly strengthens and by lag \(-10\) days in Fig. 3b) there is a noticeably strong subtropical jet between 120°E and 80°W.

In just ten days (Fig. 3c), the maximum winds in the STJ have increased over a broad region to a value of 35 m s\(^{-1}\) that stretch from 160°E to 120°W. However, as the STJ gains strength, the PFJ weakens at latitudes where the two jets are collocated. In addition, by this lag, a northwest–southeast (NW–SE) oriented band of strong zonal winds has developed which connects the STJ and PFJ. In this study, we refer to this NW–SE zonal wind band as the tilting branch. One end of this tilting branch meets the STJ at 30°S, 120°W, and the
other end joins with the PFJ at the southern tip of South America. The STJ and PFJ, together with the tilting branch, form a spiral structure that extends from 30°C, 120°W to 50°C, 120°E, even though another protrusion exists off the east coast of South America, at approximately 35°C.

Ten days later, on lag +10 days, the NW–SE-tilting branch melds with the protrusion off the east coast of South America, making the branch a much smoother transition from the STJ to the PFJ (Fig. 3d). Because of the smoother tilting branch, the spiral also becomes smoother and more noticeable. Throughout the autumn, the STJ gains strength, stretching from 110°E to 150°W by lag +30 days (Fig. 3e). In addition, between 120°E and 175°W and at approximately 55°C, a weaker 25 m s⁻¹ local maximum begins to break away from the main flow of the PFJ. This local maximum is near Antarctica, surrounded by a thick, black box in Fig. 3. The process that drives this feature differs from the rest of the PFJ. James (1988) and Bals-Ellsholz et al. (2001) demonstrated that this local maximum is caused by zonally localized Antarctic thermal forcing.

By the beginning of the austral winter, the maximum winds in the STJ exceed 45 m s⁻¹ (Fig. 3f). The jet also occurs farther westward with the 30 m s⁻¹ winds extending from 50°E to 100°W, or from the central Indian Ocean to the eastern Pacific Ocean. By the end of July, a similar pattern remains (Fig. 3g); however, the NW–SE branch over South America is no longer apparent. Finally, in late austral spring, the STJ maximum weakens to 25 m s⁻¹, and the PFJ begins to return to its annular structure (Fig. 3h).

In summary, during the austral summer, the PFJ is the lone jet in the SH, forming an annular ring at 50°C. During the autumn, the STJ begins to form at 30°C and quickly gains strength. After the development of the STJ, a NW–SE tilting branch emerges between 120° and 60°W, which connects to both the STJ and PFJ to form the spiral. The spiral persists through June. During the winter season, the STJ remains dominant. Fi-
nally, in the spring, the STJ weakens and the PFJ regains its former location and strength, as seen earlier in the summer.

b. Zonal momentum budget

To identify which terms account for the spiral-jet formation, the time evolution is analyzed for each term of the zonal momentum budget. This is accomplished by performing a pattern correlation between each term on the rhs of (1), and the zonal wind tendency, \( \partial u/\partial t \). Since the primary interest of this study is in the spiral formation, the correlation only uses the area where the tilting branch forms, which is from 120° to 60°W and from 25° to 60°S.

Amongst the nine terms in the unfiltered zonal momentum budget, the most important term is the zonal advection of zonal momentum, \([u/a \cos \phi \partial u/\partial \lambda] \), referred to as the ZMA term for the remainder of this paper. During the formation of the tilting branch, this term has an average pattern correlation of 0.603, with a maximum of 0.728 on lag 0 day, whereas the other eight terms have extremely low and negative correlations (Table 1). During the same time period, the main contributors to the negative correlations are the Coriolis term \((f v)\) and the curvature term \((u v \tan \phi/a)\), indicating that the ZMA term is balanced primarily by the sum of these two terms. Additional pattern correlations, using the high- and low-pass filtered data, indicate that two terms, \([u_{2}/a \cos \phi \partial u_{2}/\partial \lambda] \) and \([u_{2}/a \cos \phi \partial u_{2}/\partial \lambda] \), greatly contribute to the temporal change of the zonal wind (not shown).

Figure 4 shows the contribution by the ZMA term (shading) overlaid by the zonal wind tendency (contours) for the entire western hemisphere, which includes the tilting branch. Lag –6 days through +1 day are chosen because this is the time when the tilting branch forms. Before the tilting branch develops there is little to no overlap of the two terms (not shown). However, by lag –6 days, the two terms become more similar, and the correlation grows stronger as the terms approach lag 0 day. After the spiral forms (Fig. 4g), there is little change in the zonal wind, resulting in \( \partial u/\partial t \) being small in this region, while the ZMA term remains strong as it contributes toward maintaining the spiral (Fig. 4h).

c. Structure of the eddies

As described above, the ZMA term is the largest contributor to the formation of the tilting branch. The tilting branch formation process takes place within about a 6-day period. This indicates that the tilting branch is not the direct result of a thermally direct overturning circulation, rather it must be eddy-driven as implied by the above budget analysis. To help understand the physical processes represented by the low-pass ZMA term, Ertel’s potential vorticity (PV) is examined on the 340-K surface. Composite calculations with all 40 yr of data are not performed. Instead, the 10 yr that have the highest pattern correlations in the zonal wind field are used to produce a composite PV field (Fig. 5). This is because, with the exception of the years with the highest pattern correlations, there is substantial interannual variability in the location of the wave breaking.

<table>
<thead>
<tr>
<th>Term</th>
<th>Lag –4</th>
<th>Lag –3</th>
<th>Lag –2</th>
<th>Lag –1</th>
<th>Lag 0</th>
<th>Lag +1</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \left( \frac{u}{a \cos \phi} \frac{\partial u}{\partial \lambda} \right) )</td>
<td>0.492</td>
<td>0.603</td>
<td>0.659</td>
<td>0.702</td>
<td>0.728</td>
<td>0.435</td>
</tr>
<tr>
<td>( \left( \frac{u}{a \cos \phi} \right) \frac{\partial u}{\partial \phi} )</td>
<td>0.107</td>
<td>0.140</td>
<td>0.073</td>
<td>–0.131</td>
<td>–0.254</td>
<td>0.080</td>
</tr>
<tr>
<td>( \left( \frac{\partial u}{\partial \lambda} \right) \left( \frac{u}{a \cos \phi} \right) )</td>
<td>0.185</td>
<td>0.276</td>
<td>–0.011</td>
<td>–0.122</td>
<td>–0.111</td>
<td>–0.188</td>
</tr>
<tr>
<td>( \left( \frac{\partial}{a \cos \phi} \right) \frac{\partial}{\partial \lambda} )</td>
<td>0.035</td>
<td>0.012</td>
<td>0.023</td>
<td>0.056</td>
<td>0.029</td>
<td>0.041</td>
</tr>
<tr>
<td>( \left( \frac{u v \tan \phi}{a} \right) )</td>
<td>0.206</td>
<td>–0.056</td>
<td>–0.106</td>
<td>–0.169</td>
<td>–0.373</td>
<td>–0.507</td>
</tr>
<tr>
<td>( RT \frac{u \omega}{F_{g}} )</td>
<td>–0.335</td>
<td>–0.313</td>
<td>0.029</td>
<td>–0.060</td>
<td>0.041</td>
<td>0.261</td>
</tr>
<tr>
<td>( (f v) )</td>
<td>–0.048</td>
<td>–0.153</td>
<td>–0.178</td>
<td>–0.257</td>
<td>–0.397</td>
<td>–0.352</td>
</tr>
<tr>
<td>( RT \frac{f \omega}{F_{g}} )</td>
<td>–0.084</td>
<td>–0.118</td>
<td>0.204</td>
<td>0.107</td>
<td>0.134</td>
<td>0.223</td>
</tr>
<tr>
<td>( F_{e} )</td>
<td>0.052</td>
<td>0.002</td>
<td>0.004</td>
<td>0.014</td>
<td>0.044</td>
<td>0.007</td>
</tr>
</tbody>
</table>
At early lags, during the austral summer, the PV field is zonally uniform, and has a weak meridional gradient (Fig. 5a). At around lag ~20 days (Fig. 5b), a northwest to southeast tilt begins to form with a strong PV gradient, which parallels the tilting branch of the jet. In addition, wave breaking becomes stronger in two areas where the PV gradient remains weak: between 60°E and 150°E in the Indian Ocean and between 60°W and the Greenwich meridian over South America and the Atlantic Ocean. The strong breaking is highlighted by the thicker contours. Associated with the breaking over the Indian Ocean, a tight PV gradient forms that stretches from Australia, across the Pacific, to the mid-Atlantic. Over the southern Indian Ocean, the wave breaking continues, but weakens, from lag ~20 days to ~10 days, but the tight gradient remains (Fig. 5c). The breaking
over South America and the Atlantic Ocean becomes stronger over the next five days (Fig. 5d). In the vicinity of the aforementioned breaking, a smaller scale wave breaking feature can also be seen over and slightly downstream of the Andes. This small scale feature presumably reflects an orographic effect. However, as will be discussed in section 4, it is highly unlikely that such an orographic effect is an important element of the spiral-jet dynamics.

The 10-yr composite PV fields suggests that $[(u_j/a \cos \phi)(\partial u_j/\partial \lambda)]^j$ reflects wave breaking and mixing of synoptic-scale waves. This is consistent with the findings of Benedict et al. (2004) concerning low-frequency eddies. They find that the formation of both the positive and negative phases of the North Atlantic Oscillation (NAO) begins with high-frequency eddies which slow down during their eastward propagation. The waves then break and low-frequency eddies are generated.

To further investigate this possibility, the wave structure on a 2- to 10-day time scale is examined. For this purpose, the 275-hPa streamfunction field from the entire 40-yr of reanalysis data is used to construct one-point correlation maps for the austral autumn, based on lag 0 day. An example of this wave propagation is shown in Fig. 6, which uses a base point at $50^\circ S$, $101^\circ W$. The shading represents areas that are statistically significant at the 95% confidence level. Wave packets can be seen propagating from the PFJ at $180^\circ$, northeastward toward the region where the tilting branch formation takes place. As the waves pass into this region, they become somewhat more zonally elongated. As eddies become zonally elongated, through the relationship $u = -\partial \psi/\partial y$, where $\psi$ is the streamfunction, it can be inferred that the zonal wind strength must be increasing. This wave structure is also consistent with the wave breaking seen in the PV field.

In addition to the horizontal structure of the eddies, the change in phase speeds sheds additional insight into the budget result. Waves traveling along the PFJ travel relatively quickly, but as they approach the tilting branch, they begin to slow, or even become stagnant. A
dominate the ZMA term. Thus, the PV and the one-point correlation fields, taken together, suggest that the tilting branch arises from breaking waves which originate as synoptic-scale waves along the PFJ.

d. Variability of the eddy structure

To test whether the wave propagation from the PFJ toward the tilting branch does not occur at all longitudes, base points along the same latitude as that in Fig. 6 but at different longitudes are also analyzed. One example is shown for the base point at 50°S, 109°E (see Figs. 7a–e), far to the west of the base point in Fig. 6. Waves are again seen propagating along the PFJ but there are also signs of propagation toward the STJ as the waves stretch equatorward at around 100°E. However, the waves all continue to propagate at a relative high speed and show little zonal elongation, as opposed to the waves over the tilting branch seen for the former base point. Similar behavior occurs at other longitudes that were analyzed.

To examine wave fields in the vicinity of the tilting branch at other time periods, similar one-point correlation maps are constructed, using the same reference point (50°S, 101°W), but on different lag days. Figures 7f–j use the base point at 50°S, 101°W on lag +60 days. This lag corresponds roughly to the end of June, which also marks the change to austral winter. During the winter period, the wave packets have a stronger signal and propagate more rapidly along the PFJ. There is some elongation near the tilting branch, but these wave packets are moving much faster than those seen in the other correlation maps.

In summary, base points relatively close to and upstream of the tilting branch show a pronounced NW–SE tilt. At the same time, the waves, upon entering this region, begin to propagate extremely slowly and become almost stationary. This slow propagation is only seen around the time when the tilting branch is forming and not at earlier or later lags.

e. Vertical structure

As seen above, the PV field and the one-point correlation maps strongly suggest that the tilting branch is established through synoptic-scale wave breaking. The vertical structure of the zonal wind provides further evidence that the spiral is an eddy-driven feature of the jets.

For eddy-driven upper-level westerlies, such as the PFJ, the accompanying meridional circulation takes on the form of a thermally indirect circulation. This thermally indirect circulation enables the westerlies of the PFJ to penetrate much deeper toward the surface. In
contrast, the STJ can only be seen in the upper troposphere since it is associated with the thermally direct Hadley circulation. Therefore, the vertical structure of the zonal winds can be used to infer whether upper level winds are eddy-driven, or are driven by a thermally direct, overturning circulation. As shown in Fig. 8a, the STJ, the PFJ, and the tilting branch can all be seen on the 275-hPa surface on lag 0 day. At 475 hPa, the STJ is weaker, while the tilting branch and PFJ remain strong (Fig. 8b). At 575 hPa, most of the STJ disappears, except for the maximum where the spiral begins, leaving only the PFJ and the tilting branch. Farther down, at 675 hPa, the tilting branch is still seen, and the STJ is no longer present. This contrast in vertical structure between the STJ and the tilting branch provides further evidence that the NW–SE tilting branch is indeed eddy driven.

This vertical structure suggests that the downstream half of the STJ, located over the western Pacific, is also influenced by eddies. This is consistent with Blackmon et al. (1977) and Nakamura and Shimpo (2004). Blackmon et al. (1977) find that the downstream half of the African–Asian jet in the NH is driven by eddies, while Nakamura and Shimpo (2004) find that the eastern exit region of the STJ in the SH has low-level baroclinicity. This suggests that, starting from the STJ over the Indian Ocean, the jet-driving process undergoes a gradual transition, from the angular momentum transfer by a local Hadley circulation, to eddy momentum flux convergence.

**Fig. 7.** As for Fig. 6, except that the base point is 50°S, 109°E in (a)–(e), and the reference day is lag +60 days in (f)–(j).
4. Model experiments

The observations described above suggest that the jet spiral arises as a result of the formation of the tilting branch which connects the zonally confined STJ to the PFJ. This raises the question as to whether the spiral formation is a robust feature that is to be expected provided there is a zonally confined STJ. Since the STJ is driven by tropical diabatic heating, however, it is also possible that a response to the diabatic heating, other than the STJ, may play an important role in the formation of the spiral. Another viable possibility is that the spiral formation critically hinges on the zonally inhomogeneous lower boundary conditions. To evaluate these potential mechanisms, an idealized numerical model is used to perform two sets of experiments. For both sets, the lower boundary condition is zonally uniform. Therefore, the third possibility may be ruled out if these models can produce a spiral jet.

The first of the two sets of experiments is comprised of forced-dissipated runs (FD). The FD set is used to test if this idealized model is capable of mimicking the observed jet evolution, in response to zonally confined tropical heating. This tropical heating is designed to model the diabatic heating over the tropical western Pacific. The second set is comprised of initial-value calculations (IVC), and tests if a localized STJ is the direct cause of the spiral formation.

a. Model description

The numerical model is a global spectral primitive equation (PE) model which is based on the dynamic core of the Geophysical Fluid Dynamics Laboratory general circulation model (e.g., Kim and Lee 2001; Son and Lee 2005, hereafter SL05). The horizontal resolution is truncated at rhombooidal 30. In the vertical direction, 10 equidistance sigma levels are used. This model is forced by relaxing the temperature field toward a radiative equilibrium profile, with a time scale of 30 days. The radiative equilibrium profile is described in the appendix. The model includes scale-selective, eighth-order, horizontal diffusion, and nonlinear surface friction. The model configuration and parameters used in this study are exactly the same as those used in SL05 except for the horizontal resolution (see SL05 for details).

b. Forced-dissipated run

Starting with a fully developed three-dimensional flow, a prescribed, localized tropical heating, \( Q \), is gradually turned on over a 5-day period. The tropical heating field is described in the appendix. The initial three-dimensional flow is an arbitrarily chosen snapshot, taken from one of the PE model runs in SL05. This run, to be referred to as the reference run, has weak tropical heating \( (0.33 \text{ K day}^{-1}) \) and strong high-latitude cooling \( (0.83 \text{ K day}^{-1}) \). This particular model run is chosen because its zonal-mean zonal wind field, in its statistically steady state, resembles that during the SH equinoctial conditions. As shown in SL05, it is characterized by a distinct double jet with a STJ at \( \sim 30^\circ \text{S} \) and a PFJ at 55°S. (The corresponding radiative equilibrium temperature profile, \( T_{eq} \), is illustrated in Fig. A1(a)).

An ensemble of 25 realizations is calculated, where each of the 25 members differs from each other in the
Figure 9a displays the initial distribution of the ensemble-mean zonal wind at 250 hPa, $u^m_{250}$, where the superscript $m$ denotes the ensemble mean. The maximum value of $Q$, $A_Q$ in (A2), is set equal to 3 K day$^{-1}$. This value is chosen based on the observation that the April-mean maximum diabatic heating rate over the Pacific warm-pool ranges from 2 to 3 K day$^{-1}$. Superimposed on Fig. 9a is the $Q$ distribution on the 350-hPa surface. Reflecting the fact that the reference run is driven by a zonally symmetric forcing, the initial $u^m_{250}$ field is close to being zonally symmetric.

This symmetry is maintained during the first 25 days (Fig. 9b). By day 50, between 120°W and 0°, the weak STJ is replaced by a NW–SE-tilting branch which connects the strong STJ to a strengthening PFJ (Fig. 9c). The overall structure of the jet is quite similar to that seen in the observations (cf. Fig. 9c with Fig. 3d). The exception is found in the vicinity of the date line where observations show a PFJ. This region is indicated by the box inserted in Figs. 3e–g. This discrepancy arises from the fact that the idealized model does not include asymmetric forcings at high latitudes. As indicated earlier, James (1988) and Bals-Elshtain et al. (2001) showed that the tilted split jets in that region are caused by zonally localized Antarctic forcings.

While the above result suggests that the spiral jet is induced by localized tropical heating, further integration indicates that the spiral jet is only a transient solution. A comparison between Figs. 9c,d shows that the PFJ gradually shifts equatorward, eventually turning the spiral into a single broad jet (Fig. 9e). This jet structure somewhat resembles the SH winter jet shown in Figs. 3g,h. Although there is no seasonal cycle in the model, the time scales for the spiral-jet formation and demise are comparable to those in the observations.

Given the arbitrariness of the heating profiles and background fields, additional sets of model runs are performed. The results are briefly described here. It was found that a spiral jet still forms when the maximum value for $Q$ is set equal to 2.0 K day$^{-1}$. However, it is no longer realized when the maximum value drops to 1.0 K day$^{-1}$. The formation of the spiral is also sensitive to the reference state. The spiral no longer forms if a broad single jet is used as a reference state. These results indicate that in order for a spiral jet to form, the localized STJ must be sufficiently strong, and the extratropical baroclinic zone must be sufficiently broad.

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1 In this run, the additional tropical heating rate is 0.33 K day$^{-1}$, and the high-latitude cooling rate is 0.0 K day$^{-1}$. 

initial flow field. The 25 initial fields are taken from model days 1200 through 6000, with a 200-day interval. Since both $T_e^{FD}$ and $Q$ are symmetric across the equator, the ensemble mean is calculated using data from both hemispheres, yielding a total of 50 ensemble members.
The latter condition allows the PFJ to separate from the STJ.

c. Initial-value calculations

Having been able to simulate the spiral jet with the localized tropical heating, we next test whether the spiral formation can be realizable with a localized STJ, but without the tropical heating. This setup is unrealistic, but allows one to test if the spiral arises from the transient eddy response to the localized STJ, rather than from the heating itself (cf. Chang 1995). As stated earlier, this possibility is tested with a set of initial-value calculations. In these calculations, both the radiative relaxation and surface friction are removed, but the hyperdiffusion is included. Such an approach is analogous to idealized baroclinic life cycle calculations (e.g., Simmons and Hoskins 1978).

The background field is constructed by combining two different axisymmetric states, one with a weak STJ, and the other with a strong STJ. Both states are obtained from the axisymmetric version of the PE model. The weak (strong) STJ state is a steady-state solution to the model with \( T_{\text{STJ}}^{\text{NC}} (T_{\text{STJ}}^{\text{VC}}) \) as described in the appendix. These two radiative equilibrium temperature fields are shown in Fig. A1b, and their exact forms can be found in the appendix. From these two axisymmetric states, a third state is constructed. In this third state, a longitudinal sector of 100° width, centered at 170°, is prescribed with the strong STJ state. The remaining area is prescribed with the weak STJ state. The two boundaries are then smoothly matched. Figure 10a shows the resulting background field. Since such a zonally varying, artificially constructed background field is unbalanced, to prevent a drift of this background field, a forcing term is added to the model equations, as described in James et al. (1994) and Franzke et al. (2004). In a benchmark integration for which no perturbations are added to this initial state, this model setup maintains the initial state for approximately 20 model days.

Following Branstator (1995), transient eddies are excited with random initial perturbations. These perturbations are added to every grid point within the boxed area shown in Fig. 10a. To allow for rapid nonmodal growth, the perturbations are applied at all levels with a maximum value of 10 m s\(^{-1}\) at \( \sim 350 \) hPa (see the appendix). Although not shown, an integration with perturbations only at the surface produces similar jet evolution, except that the entire evolution is delayed by about six days. As for the forced-dissipative runs, 25 realizations are used to construct an ensemble mean state. The 25 members differ from each other in their initial random perturbations.

Figures 10c–h show the temporal evolution of the total eddy energy, integrated over the entire hemisphere, is also illustrated in Fig. 10b. It can be seen that as the eddies grow, \( u_{E}^{1450} \) starts to deviate from its initial state, particularly at the jet exit region (Figs. 10c–e). When the eddy energy reaches its maximum value at day 16, the westerly jet appears as a distinct spiral (Figs. 10f–h). The overall structure is quite similar to that in Fig. 9c, suggesting that a spiral jet results from eddy fluxes organized by a localized STJ.

A series of sensitivity tests further supports the above conclusion. With zonally symmetric background fields, the model is perturbed with the same initial perturbations. Although not shown, none of the runs examined generates a spiral jet. The sensitivity to the local STJ strength is also tested. Two strong STJ states with differing intensities are used to prescribe the local STJ of the background flow. These strong STJ states are produced by varying the value of the additional heating rate \( \mathcal{H}(\varphi, \sigma) \) in Eq. (A5). In the first case, the value of \( \mathcal{H} \) was increased to 2.0 K day\(^{-1}\), and in the second case it was reduced to 0.25 K day\(^{-1}\). While the first case yields a spiral jet, the second case does not (not shown). These results again suggest that the formation of the spiral jet hinges on the occurrence of a localized STJ of sufficiently strong intensity.

5. Conclusions and discussion

During the austral autumn, the upper-tropospheric westerlies in the SH take on the form of a spiral. The formation mechanism of this jet spiral is investigated in this study, utilizing both observational data analysis and numerical model experiments.

The zonal momentum budget of the NCEP–NCAR reanalysis dataset indicates that the \( \left[ \left( u \right) \left( a \cos \phi \right) \left( \partial u / \partial \lambda \right) \right] \) term is the main contributor to the formation of the NW–SE-tilting branch, which connects the STJ and PFJ to form the spiral. The time evolution of this term further indicates that this tilting branch forms on a subseasonal time scale. Analyses of Ertel’s PV, as well as one-point correlation maps of high-frequency streamfunction suggest that the spiral formation arises as transient eddies break at the downstream end of the localized STJ.

The above conclusion from the observations is supported by idealized numerical model experiments. These calculations also provide the following additional findings.

1) The tilting branch always forms at the downstream end of the localized STJ, producing a jet that spirals cyclonically toward the pole.

2) This spiral-jet solution can be obtained only if the
localized STJ is sufficiently strong, and if the latitude of the eddy-driven PFJ is sufficiently higher than that of the STJ.

3) The spiral jet is a transient solution.

Finding (1) suggests that the cyclonic jet spiral, observed in both the SH and NH, is a dynamically robust feature. Furthermore, from (1), (2), and from the observed PV fields, we may speculate as to why the jet spiral is cyclonic. Since there is a greater tendency for extratropical waves to propagate toward the equator than toward the poles (e.g., Edmon et al. 1980), the preferred orientation of the waves must be NW–SE in the SH, and NE–SW in the NH. Therefore, if the tilting branch indeed arises from breaking waves, it must also form with the same orientation as the waves. The question then is why the wave breaking tends to occur at the downstream, rather than the upstream end of the local STJ. For the answer to this question, we turn to the fact that wave breaking occurs within regions of weak westerlies, or weak PV gradients (e.g., Nakamura and Plumb 1994). Since waves propagating into the downstream end of the STJ must transit through weak westerlies centered around New Zealand, the region in the midlatitudes where the zonal winds are weakest (see Fig. 3), waves entering this region are more prone to break than those at the upstream end of the STJ. Testing this hypothesis will require careful analyses, along the lines of contour dynamics studies.

The third point suggests that the lack of a dominant
spiral structure during the austral winter may be caused by the fact that the zonal wind field has reached a new statistically steady state, and not because of differences in forcings associated with the seasonal cycle. This raises a question as to what prevents the spiral jet from being a steady-state solution. An explanation may be offered by considering the temporal evolution of the midlatitude storm tracks. Previous studies show that, in response to a strengthening STJ, both the storm track and the PFJ gradually shift toward the equator (Chang 1995; Robinson 2002; Seager et al. 2003). Similar behavior can be seen in Fig. 11, which shows the time evolution of the anomalous 275-hPa storm track and zonal winds, where the storm track is measured by the standard deviation of high-pass-filtered meridional wind $s(v_m)$, and the anomaly is defined as the deviation from the annual mean. Up until lag $-10$ days, the negative and positive anomalies of both the zonal wind and storm track are collocated (Figs. 11a,b). At the lag 0 day, the formation of the STJ causes a change from negative to positive zonal wind anomalies between 25° and 40°S (Fig. 11c), while the storm track still contains negative anomalies at this location. After a transitional period (Fig. 11d), positive storm track anomalies start to establish along the STJ (Figs. 11e,f). Once this equatorward shift of the storm track begins, it occurs at practically all longitudes (Figs. 11g,h). This time period of the equatorward shift in the storm track corresponds to the period during which the spiral-jet structure gradually disappears (cf. Figs. 3e–g). While the under-

![Fig. 11. The 40-yr composite of 275-hPa zonal wind deviation from its annual mean (shading), and the composite of 275-hPa storm track deviation from its annual mean (contours), for lag days (a) $-70$, (b) $-10$, (c) 0, (d) $+10$, (e) $+20$, (f) $+30$, (g) $+50$, (h) $+90$, and (i) $+210$. The contour interval for the zonal wind is 2 m s$^{-1}$ and that for the storm track is 1 m s$^{-1}$. Dotted contours and lighter shading represent negative values.](image-url)
lying mechanism is not fully clear to us, such an equatorward shift of the storm track eddies must gradually eliminate the latitudinal gap between the STJ and the PFJ, ultimately resulting in a single broad jet.

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APPENDIX

Model Parameters

a. Forced-dissipative run

The radiative equilibrium temperature profile of the reference run, used in the FD, is identical to that used in SL05. Therefore, readers are referred to Eq. (1) in SL05 for the precise expression of the profile. For brevity, only a schematic description is provided. The equilibrium temperature profile is constructed by adding high-latitude cooling ($C$) and tropical heating ($H$) to a base profile ($T_{\text{base}}$):

$$T_{e}^{FD}(\mathcal{H}, \varphi, \sigma) = T_{\text{base}}(\varphi, \sigma) + \Delta T_{1}(\mathcal{H}, \varphi, \sigma).$$

(A1)

As shown with the solid contours in Fig. A1a, the base profile is essentially that in Held–Suárez (Held and Suárez 1994). The values of $C$ and $H$ used in section 5b are 0.83 and 0.33 K day$^{-1}$, respectively. The corresponding $T_{e}^{FD}$ profile is also shown in Fig. A1a.

The structure of $Q$ in the FD is prescribed as below:

$$Q(\lambda, \varphi, \sigma) = A_{1} F(\lambda) G(\varphi, \sigma),$$

(A2)

where

$$F(\lambda) = \begin{cases} \cos^{2}\left[\frac{\pi(\lambda - \lambda_{w})}{2W_{\lambda}}\right] & \lambda_{w} - W_{\lambda} \leq \lambda \leq \lambda_{w} \\ 1 & \lambda_{w} < \lambda < \lambda_{e} \\ \cos^{2}\left[\frac{\pi(\lambda - \lambda_{e})}{2W_{\lambda}}\right] & \lambda_{e} \leq \lambda \leq \lambda_{e} + W_{\lambda} \\ 0 & \text{otherwise}, \end{cases}$$

(A3)

and

$$G(\varphi, \sigma) = \begin{cases} \cos^{2}\left(\frac{\pi\varphi}{2W_{\varphi}}\right) \exp\left[-\frac{(\sigma - \sigma_{0})^{2}}{2W_{\sigma}^{2}}\right] & -W_{\varphi} \leq \varphi \leq W_{\varphi} \\ 0 & \text{otherwise}, \end{cases}$$

(A4)

The two reference longitudes, $\lambda_{w}$ and $\lambda_{e}$, are set to 125° and 205°, respectively. The values for the parameters $W_{\lambda}$ and $W_{\varphi}$, which determine the horizontal scale of the localized heating, are set equal to 30° and 15°, respectively. The vertical profile is controlled by $W_{\sigma}$. The value for this parameter is 0.3 for $\sigma > 0.35$, and is otherwise equal to 0.1. For the main result of section 5b, the amplitude $A_{1}$ in (A2) is set equal to 3 K day$^{-1}$.

b. Initial-value calculations

As discussed in the main body of the text, the initial flow field is derived by combining two different zonally symmetric states. These two states can be written symbolically as

$$T_{\psi, w}^{IVC}(\mathcal{H}, \varphi, \sigma) = T_{\text{base}}^{IVC}(\varphi, \sigma),$$

and

$$T_{\psi, c}^{IVC}(\mathcal{H}, \varphi, \sigma) = T_{\text{base}}^{IVC}(\varphi, \sigma) + \mathcal{H} G(\varphi, \sigma),$$

(A5)

where $T_{\psi, w}^{IVC}$ and $T_{\psi, c}^{IVC}$ correspond to zonally symmetric states with weak and strong STJs, respectively. As such, the heating for the strong STJ state depends on the
function $G$ in (A4). Given the same value of $\mathcal{H}$ the IVC result with $\Delta T_s$ in Eq. (A1) is indistinguishable from that with $T_{\text{base}}^{\text{IVC}}$ (not shown).

The base profile, $T_{\text{base}}^{\text{IVC}}$, again resembles that of Held and Suarez (1994), but is slightly different from $T_{\text{base}}$. For $T_{\text{base}}^{\text{IVC}}$ the value of the stability parameter $\alpha$ in Eq. (1) of SL05 is set equal to 1. This base profile is indicated with the solid contours in Fig. A1b. A comparison between the base temperature fields in Figs. A1a,b shows that the meridional temperature gradient in the upper troposphere is greater for $T_{\text{base}}^{\text{IVC}}$. This upper-level baroclinicity helps the baroclinic eddies to grow faster. A relatively rapid growth is desirable for the IVCs since the time scale of this growth must be much smaller than that of the model drift (see section 5c). Figure A1b also displays the $T_{\epsilon}^{\text{IVC}}$ profile for $\mathcal{H} = 1.00$ K day$^{-1}$, which is used for generating the strong STJ circulation.

The random perturbations used in the IVC are added onto the area that extends from 6° to 41° in latitude, and from 90° to 161° in longitude. Its vertical structure is defined by the function $P(\sigma)$:

$$P(\sigma) = A_\mu \cos^{\epsilon} \left( \frac{3\pi \sigma_l - \sigma}{4 \sigma_l} \right),$$

where $\sigma_l$ and $\sigma$ mark vertical boundaries within which the random perturbations are introduced. The values chosen are 0.35 and 0.95, respectively. For the main experiment presented in section 5c, the amplitude, $A_\mu$, is set equal to 10 m s$^{-1}$.

REFERENCES


