LOCAL ENERGETICS DIAGNOSTICS IN REAL TIME

by

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ABSTRACT

A method for the calculation and display of twice daily, real-time local energetics diagnostics is described along with brief analyses of several examples captured from output of the real-time system. Specific analyses include those of the life cycles of long-lived wave packets, the Presidents’ Day Storm of 2003, and, for the first time from an energetics perspective, a blocking anticyclone. The results of these analyses demonstrate that downstream development cannot fully explain the evolution of either the Presidents’ Day Storm or the blocking anticyclone. The utility of real-time local energetics diagnostics for some short- and medium-range forecasting applications is also discussed.
1. Introduction

In a recent paper, Decker and Martin (2004) employed local energetics diagnostics and baroclinic wave packet theory to explain the stark differences observed during the decay stages of two powerful midlatitude cyclones that occurred consecutively over North America in April 2001. Those diagnostics, based on a body of work by Orlanski and collaborators that is summarized by Orlanski and Sheldon (1995) and Decker and Martin (2004), may have some utility toward forecasting in the short to medium range, as Orlanski and Sheldon (1993, 1995) and Chang (1999) have mentioned. This potential utility is thought to arise from the existence of coherent baroclinic wave packets, which have been described observationally by Lee and Held (1993), Chang (1999, 2000, 2001), and Hakim (2003), and theoretically by Yang (1991). However, studies that directly address the relevance of local energetics diagnostics to predictability have yet to be performed.

As a first step towards demonstrating their applicability to forecasting, local energetics diagnostics must first be made available in real time. A clear advantage of such availability is that one may examine notable weather events from the energetics perspective, at least cursorily, before a thoroughly quality-controlled model analysis or reanalysis is available. Real-time access to such analyses may allow synopticians and theoreticians to understand the connections between local energetics, the dynamics of baroclinic life cycles, and elements of the sensible weather more completely. For example, with such access the dependence of a particular weather system’s evolution on downstream development or some other energetic process might be assessed as the system develops.

This note describes the development of such a real-time local energetics diagnostics system, currently available to the public through the World Wide Web\(^1\). Section 2 describes the analysis

\(^1\) [http://speedy.aos.wisc.edu/~sgdecker/realtimerealtime.html](http://speedy.aos.wisc.edu/~sgdecker/realtimerealtime.html)
procedures undertaken by the real-time system. Sections 3 and 4 provide a flavor of the output available on the website. Section 3 focuses on wave packet observations, while Section 4 presents a few examples of weather events captured by the real-time system, including, for the first time, the life cycle of a major blocking anticyclone. Finally, Section 5 offers a discussion and conclusions.

2. Data analysis procedure

The construction of the real-time diagnostics is performed in a manner similar to that employed in the retrospective diagnostics described by Decker and Martin (2004). The following differences should be noted, however. The real-time system is based on analyses from the National Centers for Environmental Prediction Global Forecast System (GFS) provided through Unidata’s Internet Data Distribution system. Diagnostics are computed twice daily from the 00 UTC and 12 UTC analyses, and are available within six hours of the analysis time. Since the diagnostics are constructed in real time, a 28-day lagged mean is used. The GFS analyses, and thus the resulting energetics diagnostics, are thinned to a cylindrical equidistant grid with 2.5° spacing in both the zonal and meridional directions, with 10 vertical levels². Vertical motion fields are available neither below 850 hPa nor above 300 hPa and are assumed zero at those levels. Eddy kinetic energy (EKE) and its tendency terms are displayed as vertical averages, as in Decker and Martin (2004), but the formulation is as follows:

\[
\overline{A} = \frac{1}{p_2 - p_1} \int_{p_1}^{p_2} A dp .
\]

(1)

\(A\) refers to any quantity (i.e., EKE or one of its tendency terms), and the values of \(p_1\) and \(p_2\) are taken to be 100 hPa and 1000 hPa, respectively. Although the GFS analyses are available with global coverage, energetics calculations are performed only from 20° to 85° latitude in each hemisphere.

² They are 1000, 850, 700, 500, 400, 300, 250, 200, 150, and 100 hPa.
The wave packet envelope function, on the other hand, is computed globally. Two independent assessments of the envelope function are made. The first method, complex demodulation, is undertaken following Chang (2000). The second method, recently proposed by Zimin et al. (2003), is employed with values of 4 and 11 for \( k_{\text{min}} \) and \( k_{\text{max}} \), respectively. The envelope function, which is designed to pick out wave packets in the observed flow, is described in more detail in the above references and in Decker and Martin (2004).

Care is taken when computing the mean state since occasionally the thinned GFS analysis may be partially or completely unavailable. The program used to calculate the time mean performs numerous checks so that bad data values may be flagged. This is done on a variable-by-variable, gridpoint-by-gridpoint basis so that good data may still be used in computing the mean state at times when there is incomplete data. Thus, the mean state at any given gridpoint for any given variable may truly be a 25-day mean, for instance, if there are three days for which the data were unavailable.

The real-time energetics system uses GEMPAK (the GEneral Meteorology PAckage) to produce plots covering both the Northern and Southern Hemispheres. The following plots are produced on equal area projections spanning six overlapping sectors:

- EKE, ageostrophic geopotential flux (AGF) vectors, and 300-hPa heights,
- EKE tendencies due to advection by the eddy wind,
- EKE tendencies due to AGF convergence (AGFC),
- AGF vectors and EKE tendencies due to baroclinic generation, and
- EKE tendencies due to barotropic generation.

The mathematical formulation of these terms is given in Table 1.

Hovmöller (1949) diagrams of AGFC, baroclinic and barotropic generation, and the wave packet envelope function (for both methods) are also provided. These are calculated in the same manner as
in Decker and Martin (2004). In addition, polar stereographic plots and animations of both forms of the wave packet envelope function are available. Finally, the mean 300-hPa heights are plotted, along with an indication of the percentage of data that was acceptable for use in creating the mean at the current analysis time. Physical interpretations of all the fields plotted are available on the website as well as in Orlanski and Sheldon (1995), McLay and Martin (2002), and Decker and Martin (2004).

For the real-time system to be useful, it must produce truthful diagnostics, but the lagged mean and relatively coarse resolution of the data raise the possibility that this may not be the case. A comparison of the system’s output with that previously displayed by Decker and Martin (2004) for the April 2001 storms they studied, which was based on a more careful analysis that presumably is not far from the truth, served as an assessment of the validity of the system. This comparison, although showing the real-time system at its worst (since errors due to the lagged mean should maximize during seasonal transitions), revealed that the system was consistently able to pinpoint important centers of EKE and its various tendency terms. See Decker (2003) for more details. Perhaps more importantly for forecasting, it also was able to pick out wave packets in the flow with little difficulty. However, important differences occasionally did occur, suggesting that, for an analysis of the energetics budget of any particular midlatitude system to be rigorous, it must be performed retrospectively. Thus, the cursory analyses presented in the following sections should not be taken as absolute truth, but instead as a reliable first guess regarding the true mechanisms involved during the particular situations examined.

3. Wave packet observations

Previous studies (e.g., Chang 1999) have shown that wave packets are more coherent in the Southern Hemisphere than in the Northern Hemisphere. This is because the Southern Hemisphere is mostly ocean, making topography and land-sea contrasts small contributors to the mean large-
scale flow there. In addition, the ice-ocean contrast around Antarctica is essentially zonal. As a result, the Southern Hemisphere flow is often quite zonal in the time-mean sense, which is close to the idealized theoretical situation from which downstream development theory arises. Examination of the real-time output over a number of seasons indicates that, on average, wave packets continue to be easier to detect and longer-lived in the Southern Hemisphere.

As an example, the real-time system detected a long-lived wave packet in the Southern Hemisphere (allowing for data gaps) that started around 130°W on 20 December 2002 (Day 6 in Fig. 1), circled the globe three times, and finally dissipated near 90°W around 30 January 2003 (Day 47). There is some question as to whether one wave packet ends and another begins around 25 December (Day 11) and 16 January (Day 33), but for the purposes of computing a group velocity, these possibilities will be ignored. Assuming a central latitude of 50° for the wave packet (consistent with the results of Chang 1999), the pace of the packet over the 41 days corresponds to an average group velocity of about 23 m s⁻¹. This agrees with the previous results of Chang (2000), who tracked four wave packets in the Southern Hemisphere summer of 1984–85 with group velocities of 23 (twice), 22, and 21 m s⁻¹. In contrast, both NWP model error and the leading edge of the improvement of that error from targeted observations appear to propagate downstream at speeds near 30° day⁻¹ in the Northern Hemisphere (Persson 1999, Szunyogh et al. 2002) and, for model error, 40° day⁻¹ in the Southern Hemisphere (Persson 1999). Individual troughs and ridges typically have phase speeds around 10 m s⁻¹ (Chang 2000).

Returning to Fig. 1, note that a second long-lived wave packet is captured. It makes just over one circumnavigation of the earth, beginning just west of the Date Line on 19 January (Day 36) and dissipating just east of the Date Line on 2 February (Day 50). Both wave packets met their demise

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3 30° day⁻¹ is equivalent to 25 m s⁻¹ at 49.6° latitude and greater than 25 m s⁻¹ at lower latitudes. The signals that Persson (1999) and Szunyogh et al. (2002) observed in the Northern Hemisphere were generally around 45°N.
over the Pacific Ocean west of South America. Based on regular examination of the real-time system output, this seems to be a climatologically favored region for wave packet dissipation in the Southern Hemisphere, particularly in winter (also see, e.g., Chang 1999, Fig. 9a).

The EKE plot at 1200 UTC 28 January 2003 foreshadowed the death of the longer-lived wave packet (Fig. 2). From the previous Hovmöller diagram, it is evident that at this time the wave packet extended from about 140° to 80°W. Since AGF is a measure of the group velocity of a wave packet (Chang and Orlanski 1994), a continuously propagating wave packet is characterized by downstream-directed AGF in most, if not all, portions of the wave packet. Indeed, downstream energy fluxes were observed in the western part of the wave packet in Fig. 2. (e.g., near 50°S, 130°W). However, on the northern and eastern flanks of the lead trough in the wave packet (centered near 40°S, 110°W), the energy fluxes were directed equatorward and, to the east of the trough, a strong component was westward, against the propagation direction of the wave packet. Only minor fluxes were observed in the downstream direction, just west of the southern tip of Chile for instance. Thus, in this particular case, the death of a long-lived wave packet could have been properly forecast using local energetics diagnostics alone; the lack of strong downstream AGF at the leading edge of the wave packet foretold the packet’s demise, which occurred within two days (Fig. 1).

4. Examples

We now turn to a more detailed analysis of real-time energetics output for two recent notable weather events.

a. Presidents’ Day Storm of 2003

In mid-February 2003, a snowstorm of record proportions walloped the Mid-Atlantic region of the United States. Snow was continuously observed between 0812 UTC 16 February and 1637 UTC
17 February at Baltimore–Washington International Airport (BWI), resulting in a total accumulation of 28 inches (71 cm). The EKE center associated with the storm was originally part of a large cutoff low meandering across the Eastern Pacific. Its evolution, shown in Fig. 3, is completely unlike those presented in Decker and Martin (2004).

The arrival of the upper low at the West Coast (Fig. 3a) coincided with poor forecasts in disparate locations. Rain began twelve hours earlier than the National Weather Service (NWS) forecasted in Ontario, California, on 11 February. Meanwhile, snow squalls of unanticipated intensity hit parts of southern Wisconsin. The Alberta Clipper producing the snow over the Upper Midwest was not associated with a distinct EKE maximum, although there was a region of concentrated ageostrophic geopotential fluxes just upstream of the region of heavy snow. This region of EKE did become better defined as it received energy from the opening upper low along the West Coast (Fig. 3b). The EKE center associated with the landfalling cyclone weakened as a result. Since this center received energy fluxes initially (Fig. 3a) and then radiated energy downstream two days later, the downstream development paradigm might suggest that the center would continue to weaken with time, especially since, if anything, there was upstream dispersion away from the center on its west side over the Pacific. However, this was not to be the case. Instead, despite strong downstream dispersion over the subsequent four days (Figs. 3c,d), which is only slightly compensated for by energy fluxes across Mexico on 15 April (Fig. 3c), the EKE center slowly grew, approaching its original intensity by the time of the heavy snow in the Mid-Atlantic (Fig. 3d).

Hovmöller diagrams reveal more insight into the energetic mechanisms leading to the development of the storm.\footnote{Of course, only the data shown in the bottom half of these figures were available in real time.} Although a train of alternately positive and negative AGFC appears to have propagated through the cutoff low around 12 February (Fig. 4a, near 120°W, Day 11), the
AGFC remains negative in a long strip following the EKE center over the subsequent 6 days. Also note that the EKE maximum, which exceeded 200 J kg$^{-1}$ at times between 10 February and 13 February (Days 9–12), weakened to under 100 J kg$^{-1}$ for a period before exceeding 200 J kg$^{-1}$ at the time of the heavy snow. Clearly, the convergence of downstream-directed energy fluxes did not contribute much to the development of the EKE maximum associated with the snowstorm. The region of positive AGFC just west of the EKE center during the storm is mainly a reflection of recirculation (Fig. 3d). On the other hand, baroclinic conversion’s contribution to growth was extensive in the region both before and during the storm (Fig. 4b). Most notably, however, is the barotropic conversion (Fig. 4c), which was positive prior to and during the storm, and whose appearance coincided with the redevelopment of the EKE center associated with the storm. The lack of AGF from upstream combined with the extended periods of baroclinic and barotropic conversion prior to the heavy snowfall suggest that the Presidents’ Day Storm of 2003 fits neither the downstream development nor traditional baroclinic growth–barotropic decay paradigms. In fact, this system’s life cycle does not easily conform to any existing models of which we are aware. Unfortunately, incomplete data during the decay stage of the system (reflected in the inaccurate baroclinic conversion in Fig. 4b on Day 18) precludes an examination of whether, or to what extent, barotropic processes were important to that decay.

b. Subarctic blocking high

During early March 2003, a blocking high developed and persisted over the Bering Strait. The high was notable for both its persistence (lasting about 10 days) and its circular symmetry at maximum amplitude. Fortunately, there were no data problems throughout much of the life cycle of the anticyclone, allowing for a preliminary glimpse of what processes may have led to its growth, maintenance, and eventual decay.
Most of the life cycle of the anticyclone is encapsulated in Fig. 5. The anticyclone began its development on 4 March (Fig. 5a) as a ridge located between two EKE maxima well east of Japan. Although there were some downstream energy fluxes through the ridge, there were also energy fluxes directed antiparallel to the 300-hPa geostrophic flow on the western flank of the anticyclone. These fluxes led to AGFC\(^5\) on the upstream end of the western EKE center, and thus helped to maintain the intensity of that center. Also of note were the strong northward fluxes emanating from the eastern Pacific that produced strong AGFC over the southwest coast of Alaska, leading to the development of an EKE center there on 5 March (Fig. 5b). A more important aspect of the energetics on 5 March, however, was the intense energy flux directed westward through the center of the ridge axis west of the Aleutians. In fact, much of the decay of the cutoff low to the east of the developing anticyclone (Figs. 5a–c) appears to have been due not to downstream fluxes but instead to the poleward (Fig. 5a) and upstream (Fig. 5b) AGF previously mentioned. The anticyclone cut off completely on 6 March (Fig. 5c) with two EKE centers still associated with it, one on the west side, and the other on the east side. Over the next 48 hours, the bulk of the AGF associated with the cutoff high was involved in recirculation, with only a small amount of downstream flux noted across British Columbia (Figs. 5c–e)\(^6\). The anticyclone slowly decayed over the subsequent week (Figs. 5f–i) despite continued recirculation. Downstream fluxes do not appear to have contributed appreciably to the decay until around 12 March (Fig. 5i), when downstream energy dispersion occurred over the Yukon.

\(^5\) Although available on the website, plots of AGFC are not shown here for brevity.

\(^6\) Whether AGF was directed across the Pole at these times cannot be easily determined, since the energetics grid only goes to 85\(^\circ\)N. GEMPAK will not produce polar stereographic plots with such a grid. However, the fact that no EKE centers suddenly appear north of the British Isles (not shown) suggests that any such flux was minor.
Hovmöller diagrams must be interpreted carefully for this case since they are based on a 20°–70° latitudinal average. Note that up to a third of the anticyclone was located north of 70°N during parts of its life cycle. (70°N is approximately the latitude of Alaska’s northern coast.) Despite these caveats, the diagram of AGFC and EKE (Fig. 6a) shows that no wave trains propagate east from the region of the anticyclone during its existence (note that the anticyclone occurs along the Date Line during Days 9–18); wave trains are present along and west of the Date Line, but not east of 150°W. This leads to a lack of either substantial AGFC or EKE along, for instance, 90°W. This lack of wave packet activity along 90°W actually occurs even before the formation of the anticyclone (Days 2–8) as well. Upon the decay of the anticyclone, two wave packets can be inferred from the AGFC wave trains traversing the Western Hemisphere between 120°W and 30°E, one from 14–20 March (Days 19–25, ellipse 1), the other from 20 March to the end of the period (Days 25–30, ellipse 2).

It may have been expected that the paucity of AGFC or EKE around 90°W between Days 1–17 would indicate rather quiescent weather in that region. However, the observed baroclinic conversion (Fig. 6b) indicates this was not the case. A number of systems (indicated by black streaks or blobs oriented from lower left to upper right) associated with baroclinic generation were present in the region throughout this period, and the Sullivan, WI NWS Forecast Office noted this in their afternoon forecast discussion on 3 March (Day 8), mentioning a “SUDDENLY MORE ACTIVE WX PAT.” Thus, for this period, local energetics diagnostics would have provided little forecasting utility; the absence of wave packets, eddy kinetic energy, and/or strong ageostrophic fluxes is seemingly no guarantee that the weather will be inactive.

Turning back to the anticyclone, the development of the EKE center associated with the western part of the anticyclone (indicated by the large EKE values at 160°E on Day 10 [5 March] and marked by circle 3 in Fig. 6b) was dominated by baroclinic conversion (Fig. 6b). In fact,
examination of individual EKE tendencies reveal that the baroclinic conversion was so intense in that region that the Hovmöller program filtered out a part of that conversion (leaving a blank spot in what otherwise is a continuous streak of positive tendencies), considering it to be bad data. A later streak of baroclinic generation (extending from 105°E on Day 9 to the Date Line on Day 15) did not maintain the anticyclone; it was instead associated with an EKE center that crossed the Pacific to the south of the anticyclone (visible in Fig. 5d–i). Thus, this “blocking” anticyclone apparently did not completely block the propagation of disturbances through the region, perhaps because it was so far north.

What did not contribute to the growth of the anticyclone were interactions with the mean flow. As the diagram for barotropic conversion shows, the development of the anticyclone instead coincides with barotropic decay (Fig. 6c). The region of barotropic growth indicated just west of the Date Line over the period 10–12 March (Days 15–17) is misleading, as it was partially due to barotropic growth associated with the EKE center passing through the region to the south. In addition, barotropic decay existed north of 70°N at this time (not shown), which was not considered in the preparation of the diagram.

Clearly, the cutoff anticyclone that occurred during early March 2003 is another example of a notable weather event that did not evolve according to the downstream development paradigm (except perhaps for the initial growth stage, where there was some downstream dispersion through the northern part of the ridge). The slow rate of decay this system experienced suggests that friction may have played an important role in that decay, but since the real-time system does not estimate tendencies due to friction, it is unknown how important those actually were. Other slow processes such as infrared cooling to space may have also contributed to the decay.

5. Concluding discussion
This note describes the construction of local energetics diagnostics in a real-time setting, and uses those diagnostics to illustrate example cases. The motivation behind this approach is twofold. First, it provides the groundwork for potential future forecasting applications of local energetics diagnostics. Second, it provides a tool by which the life cycles of midlatitude disturbances, and in particular the effect of downstream development on those life cycles, might be studied as they develop, at least cursorily, rather than months or years after the fact.

Output from the real-time system showed that, at least in the Northern Hemisphere, neither cyclones nor anticyclones necessarily evolve according to the downstream development paradigm, despite what previous studies, including Decker and Martin (2004), may have suggested. Indeed, it appears that a wide variety of life cycle types occur for midlatitude synoptic-scale disturbances, with those that follow from downstream development being only one type. It should be noted that neither the anticyclone event nor the snowstorm of the previous month were selected for examination because of their apparent disregard for the downstream development paradigm. Instead, they were chosen simply because they were significant recent weather events.

Since the use of a non-centered time mean does not appear to negatively affect the veracity of the results, it appears that, if there are any intrinsic forecasting applications of local energetics diagnostics, the computation of those diagnostics in real-time should be useful for those applications. One forecasting application that has been discussed in the literature for many years involves the exploitation of the fact that wave packets can exist for long periods and move at a nearly constant speed. Given the ability to detect a wave packet, a forecaster could anticipate the passage of that wave packet over regions downstream and use that information to forecast periods of active, changeable weather (when the wave packet was overhead), or periods of tranquil weather (when the flow was zonal due to the absence of a wave packet). The preliminary results presented
here suggest that this may be feasible in the Southern Hemisphere. The Northern Hemisphere, on the other hand, may have too few long-lasting wave packets for the idea to have much utility, at least in the medium range. An additional complication is that it is unclear whether the absence of a wave packet truly represents inactive weather, as was noted in section 4b.

For shorter forecast ranges, the lack of long-lived wave packets in the Northern Hemisphere may be less of a problem. Experience viewing the diagnostics day to day has shown that the conjunction of strong baroclinic generation with downstream ageostrophic fluxes is a good indicator that a trough will develop downstream, even if a robust wave packet is not present. Some instances of this can be inferred from Fig. 6. In addition, Szunyogh et al. (2002) show how local energetics diagnostics provide clues into the dynamics of NWP improvement via targeted observations.

The discrepancies between the wave packet group velocities found here and in Chang (2000) and those in Persson (1999) (at least for the Northern Hemisphere) and Szunyogh et al. (2002) might simply reflect differences in the average group velocities of wave packets in the Southern versus Northern Hemispheres. The interpretation of Szunyogh et al. that their NWP improvements were embedded within a wave packet supports this view. On the other hand, these differences may be real. The fact that the NWP improvement signal does not remain zonally confined (Szunyogh et al. (2002), their Figs. 5–6) suggests that the dynamics of model improvement are not exactly those of downstream baroclinic development. In addition, the climatology of Chang (1999, Fig. 6a) does not support such fast group velocities for wave packets in the Northern Hemisphere, at least on average. Instead, velocities less than 20 m s\(^{-1}\) are indicated over western North America, an area downstream of the targeted observations Szunyogh et al. (2002) studied. In the Southern Hemisphere, the difference between model error propagation (40° day\(^{-1}\), or about 33 m s\(^{-1}\)) and wave packet group velocity (21–23 m s\(^{-1}\)) is certainly real.
Working with the real-time energetics plots on a regular basis has raised numerous questions. A particularly vexing question concerns the manner by which the reliability and quality control of the input data might be improved. Subsequent application of the energetics diagnostics to forecasting would benefit from knowledge of some synoptic/climatological properties of the wave packets. For instance, what is the probability that a wave packet observed to exist for $m$ days will still exist after $m+n$ days (where $m$ and $n$ are integers)? Presumably, a wave packet that has lived for 30 days is more likely to remain in existence at day 32 than a wave packet that has lived for 5 days is to make it to day 7, but is this really the case? How dependent might the life cycles of wave packets be on season and hemisphere? What percentage of explosive cyclogenesis events are associated with wave packets? Although reanalysis products could be used to construct an initial climatology, perhaps the real-time system could be used to update the climatology over time. On the other hand, if one were more interested in extracting prognostic information from the real-time system, a climatology based on the real-time output may be more appropriate.

One of the critical problems impeding the ability to apply these real-time diagnostics directly to forecasting is the fact that the connection between wave packets and sensible weather is still not well developed. In at least one case described here, the absence of a wave packet was not concomitant with inactive weather. Future research is necessary to elucidate this connection, should it exist, in order for forecasting applications to be more fruitful. By allowing energetic and synoptic analyses to be viewed together, the real-time diagnostics described herein may be particularly helpful in tackling this problem.

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REFERENCES


FIGURE CAPTIONS

Fig. 1  Hovmöller diagram of the vertically and latitudinally averaged wave packet envelope function (black lines) in the Southern Hemisphere over the period 0000 UTC 15 Dec 2002–0000 UTC 6 Feb 2003. Function is labeled in m s\(^{-1}\) and contoured every 4 m s\(^{-1}\), starting at 14 m s\(^{-1}\). Complex demodulation was used to produce this example, which was created by splicing together two images from the website, one obtained on 13 Jan 2003, and the other on 6 Feb 2003. Blank regions around Days 11 and 22 are due to missing data.

Fig. 2  300 hPa geopotential heights (solid lines), vertically averaged eddy kinetic energy (EKE, shaded), and vertically averaged ageostrophic geopotential flux (AGF) vectors over the South Pacific from the real-time system at 1200 UTC 28 Jan 2003. Geopotential heights are labeled in dam and contoured every 20 dam. EKE is shaded in units of J kg\(^{-1}\) according to the legend. AGF vectors are in units of m\(^3\) s\(^{-3}\) according to the reference arrow at the lower right.

Fig. 3  (a) 300 hPa geopotential heights (solid lines), vertically averaged EKE (shaded), and vertically averaged AGF vectors from the real-time system at 1200 UTC 11 February 2003. Geopotential heights labeled and contoured as in Fig. 2. EKE labeled and shaded as in Fig. 2. AGF vectors as for Fig. 2 with reference arrow indicated. (b) As for Fig. 3a but for 1200 UTC 13 February 2003. (c) As for Fig. 3a but for 1200 UTC 15 February 2003. (d) As for Fig. 3a but for 1200 UTC 17 February 2003.

Fig. 4  (a) Hovmöller diagram of the eddy kinetic energy and ageostrophic geopotential flux convergence from 1200 UTC 7 February 2003 to 1200 UTC 20 February 2003. EKE labeled in J kg\(^{-1}\) and contoured every 100 J kg\(^{-1}\) beginning at 100 J kg\(^{-1}\). Dark (light) shading is the
AGF convergence (divergence) values less than (greater than) \(-100 \ (100) \ \text{J kg}^{-1} \ \text{day}^{-1}\). Heavy black line indicates the period and longitude of heavy snow at BWI. (b) As for Fig. 4a but dark (light) shading represents baroclinic conversion values greater than (less than) \(100 \ (-100) \ \text{J kg}^{-1} \ \text{day}^{-1}\). (c) As for Fig. 4a but dark (light) shading represents barotropic conversion values greater than (less than) \(100 \ (-100) \ \text{J kg}^{-1} \ \text{day}^{-1}\).

Fig. 5  (a) As for Fig. 3a but for 1200 UTC 4 March 2003. (b) As for Fig. 5a but for 1200 UTC 5 March. (c) As for Fig. 5a but for 1200 UTC 6 March. (d) As for Fig. 5a but for 1200 UTC 7 March. (e) As for Fig. 5a but for 1200 UTC 8 March. (f) As for Fig. 5a but for 1200 UTC 9 March. (g) As for Fig. 5a but for 1200 UTC 10 March. (h) As for Fig. 5a but for 1200 UTC 11 March. (i) As for Fig. 5a but for 1200 UTC 12 March 2003.

Fig. 6  (a) As for Fig. 4a but for the period 0000 UTC 24 February 2003 to 0000 UTC 25 March 2003. Wave packets contained within ellipses 1 and 2 are described in the text. (b) As for Fig. 4b but for the period 0000 UTC 24 February 2003 to 0000 UTC 25 March 2003. Circle 3 is referenced in the text. (c) As for Fig. 4c but for the period 0000 UTC 24 February 2003 to 0000 UTC 25 March 2003. Circle three is referenced in the text.
TABLE 1. The mathematical representation of each of the terms in the EKE tendency equation for which plots are available on the website. \( _{s} \) is the specific volume, and \( _{\beta} \) is the latitude.

Subscript \( m \) refers to a time mean field, while lowercase indicates an eddy field. Subscript 3 indicates a three-dimensional vector. Other notation is standard.

<table>
<thead>
<tr>
<th>Term</th>
<th>Formula</th>
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<tbody>
<tr>
<td>EKE</td>
<td>( \frac{u^2 + v^2}{2} )</td>
</tr>
<tr>
<td>AGF</td>
<td>( \mathbf{v} \phi - \mathbf{k} \times \nabla \frac{\phi^2}{2f(\Theta)} )</td>
</tr>
<tr>
<td>Advection by the eddy wind</td>
<td>(- \mathbf{v}_3 \cdot \nabla_3 (\text{EKE}) )</td>
</tr>
<tr>
<td>AGFC</td>
<td>(- \nabla \cdot (\text{AGF}) )</td>
</tr>
<tr>
<td>Baroclinic generation/conversion</td>
<td>(- \omega \alpha )</td>
</tr>
<tr>
<td>Barotropic generation/conversion</td>
<td>(- \mathbf{v} \cdot (\mathbf{v}_3 \cdot \nabla_3) \mathbf{v}_m )</td>
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Fig. 1. Hovmöller diagram of the vertically and latitudinally averaged wave packet envelope function (black lines) in the Southern Hemisphere over the period 0000 UTC 15 Dec 2002-0000 UTC 6 Feb 2003. Function is labeled in m s\(^{-1}\) and contoured every 4 m s\(^{-1}\), starting at 14 m s\(^{-1}\). Complex demodulation was used to produce this example, which was created by splicing together two images from the website, one obtained on 13 Jan 2003, and the other on 6 Feb 2003. Blank regions around Days 11 and 22 are due to missing data.
Fig. 2  300 hPa geopotential heights (solid lines), vertically averaged eddy kinetic energy (EKE, shaded), and vertically averaged ageostrophic geopotential flux (AGF) vectors over the South Pacific from the real-time system at 1200 UTC 28 January 2003. Geopotential heights are labeled in dam and contoured every 20 dam. EKE is shaded in units of J kg\(^{-1}\) according to the legend. AGF vectors are in units of m\(^3\) s\(^{-3}\) according to the reference arrow at the lower right.
Figure 3. (a) TOU 500 hPa geopotential heights (contours), vertically averaged EKE (shaded), and vertically averaged ACF vectors for 0000 UTC 13 February 2003. (b) As for Figure 3a but for 1200 UTC 13 February 2003. (c) As for Figure 3a but for 1200 UTC 13 February 2003. (d) As for Figure 3a but for 1200 UTC 13 February 2003. and shaded as in Figure 2. ACF vectors are for Figure 2. With reference to Figure 3, vectors in TOU show the contributions to the EKE from the real-time TOU at 1200 UTC 13 February 2003. Geopotential height isobars (solid lines), vertically averaged EKE (shaded), and vertically averaged ACF vectors.
Fig. 4 (a) Hovmoller diagram of the eddy kinetic energy and ageostrophic geopotential flux divergence from 1200 UTC 7 February 2003 to 1200 UTC 20 February 2003. EKE labeled in J kg$^{-1}$ and contoured every 100 J kg$^{-1}$ beginning at 100 J J kg$^{-1}$. Dark (light) shading is the AGF convergence (divergence) less than (greater than) -100 (100) J kg$^{-1}$ day$^{-1}$. Heavy black line indicates the period and longitude of heavy snow at BW1. (b) As for Fig. 4a but dark (light) shading represents baroclinic conversion values greater than (less than) 100 (-100) J kg$^{-1}$ day$^{-1}$. Black line in Fig. 4a is white here. (c) As for Fig. 4b but dark (light) shading represents barotropic conversion values greater than (less than) 100 (-100) J kg$^{-1}$ day$^{-1}$. 
Fig. 5  (a) As for Fig. 3a but for 1200 UTC 4 March 2003.  (b) As for Fig. 5a but for 1200 UTC 5 March.  (c) As for Fig. 5a but for 1200 UTC 6 March.  (d) As for Fig. 5a but for 1200 UTC 7 March.  (e) As for Fig. 5a but for 1200 UTC 8 March.  (f) As for Fig. 5a but for 1200 UTC 9 March.  (g) As for Fig. 5a but for 1200 UTC 10 March.  (h) As for Fig. 5a but for 1200 UTC 11 March.  (i) As for Fig. 5a but for 1200 UTC 12 March 2003.
Fig. 6 (a) As for Fig. 4a but for the period 0000 UTC 24 February 2003 to 0000 UTC 25 March 2003. Wave packets contained within ellipses 1 and 2 are described in the text. (b) As for Fig. 4b but for the period 0000 UTC 24 February 2003 to 0000 UTC 25 March 2003. Circle 3 is referenced in the text. (c) As for Fig. 4c but for the period 0000 UTC 24 February 2003 to 0000 UTC 25 March 2003. Circle 3 is referenced in the text.