Downstream development and Kona low genesis

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[1] A composite analysis of 43 Kona lows in conjunction with a case study of a particularly damaging Kona low indicate that downstream development is dynamically important to the subtropical cyclogenesis. It takes the form of eastward propagating, statistically significant upstream potential vorticity (PV) anomalies with accompanying meridional wind anomalies at the tropopause level prior to the formation of a Kona low. The downstream development culminates in the formation of a PV streamer, a meridionally-elongated stratospheric intrusion of high PV air into the troposphere, associated with a breaking wave on the dynamical tropopause. Subsequently, the streamer 'cuts off' from the stratospheric reservoir of high PV and translates equatorward, thereby providing a necessary dynamical forcing for the subtropical surface cyclogenesis.
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1. Introduction

[2] Kona lows are subtropical cyclones that form in the central Pacific during the cool season from October to April [*Simpson*, 1952; *Ramage*, 1962]. Thus, they are dynamically distinctive in that they form equatorward of the extratropical storm track, and poleward of the characteristic track of incipient tropical cyclones. Moreover, they exert a significant impact upon the climate of Hawaii, at times resulting in severe weather including flash floods, high winds, large surf and severe thunderstorms [*Morrison and Businger*, 2001].

[3] Kona low formation is dependent on the equatorward migration of an upper-level extratropical disturbance that becomes detached from the midlatitude westerly flow. Prior to being cutoff, these disturbances take the form of elongated, meridionally-oriented intrusions of high PV air *Caruso and Businger* [2006, Figure 1b] termed PV streamers [*Appenzeller and Davies*, 1992].

[4] Factors deemed important for Kona low genesis include the midlatitude jet structure, the characteristics of the upper-level cutoff and the local conditions in the genesis region [*Morrison and Businger*, 2001; *Martin and Otkin*, 2004; *Otkin and Martin*, 2004a, 2004b; *Caruso and Businger*, 2006]. Here the focus is not on the cyclogenesis itself but rather on the origin and dynamics of the precursor PV streamer that spawns the upper-level cutoff that is in turn instrumental to the surface cyclogenesis. Thus, the primary aim of the present study is to examine the dynamical role of downstream development, viewed as the propagation along a tropopause-level wave guide (sic. jet stream) of a growing wave packet [cf. *Orlanski and Sheldon*, 1993].

2. Data and Methodology

[5] *Caruso and Businger* [2006] used NCEP-NCAR Re-Analysis data to identify 43 Kona lows within the domain 10–45N, 175E–130W during the cool season from 1980 to 2002. In the present study, ECMWF Re-Analysis (ERA-40) data, interpolated onto a Gaussian grid with a nominal resolution of one degree in the horizontal and 60 vertical levels, are used to examine the formation and extension of the PV streamers in these previously identified Kona low events.

[6] Composite analyses are constructed for the 43 Kona low cases. The analyses are centered on the location and time at which the system reaches maturity [i.e. the minimum sea level pressure (SLP)]. A detailed account of the formation location and track of the individual Kona lows is given by *Caruso and Businger* [2006, Figure 5a]. Composite analyses are performed for lead times up to 96 hours prior to maturity. The rationale for the compositing is that it helps pinpoint the flow structures prevalent during Kona low events whilst excluding extraneous effects. For the composite to be effective, it requires that the development regularly exhibits a consistent and coherent space-time structure. An in-depth examination of all 43 cases insures that the results presented herein are indeed robust and that the composite structure is not dominated by a few intense outliers.

[7] There are two further points to note regarding the composites. First, due to the sphericity of the Earth, absolute distances are not conserved in the compositing procedure. Given that the dynamical features in question are primarily confined to the immediate vicinity and equatorward of the midlatitude jet, however, this effect should not unduly affect the physical interpretation of the results. Second, the main composited fields are the 250 hPa PV and meridional wind anomalies, which are defined relative to the monthly mean over the ERA-40 time period for each individual event, the 2 PVU isoline on the 250 hPa surface (to identify the dynamical tropopause), the 700 hPa diabatic heating and the SLP.

[8] The robustness of the compositing at each individual composite time is examined via a Monte Carlo calculation involving the comparison of the composited fields with 300 composites constructed with randomly selected, instantaneous ERA-40 analyses. The latter analyses are constrained to occur: i) within plus or minus 10 calendar days of an actual event, and ii) in a different year than the observed event, so as not to include the event itself in the comparison. All of the anomalies presented herein are found to be significant at or above the 95 percent significance level.

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[9] To aid in the interpretation of downstream development for a particular Kona low event, the vertically averaged kinetic energy (KE) and energy flux vectors are calculated. A full description of the relevant equations and their physical interpretation is given by *Orlanski and Sheldon* [1993, 1995]. Herein, the data is analyzed on 19 equally spaced pressure levels from 1000 to 100 hPA, with a 50 hPa resolution, and perturbation quantities are defined as the difference from the 30 day average, centered on the mature time.

3. Downstream Development: A Composite Study

[10] The composite 250 hPa fields of the PV and meridional wind anomalies, the 2 PVU isoline and select isobars for all 43 Kona low events are presented in Figure 1. The general characteristics of Kona low evolution as portrayed in Figure 1 are found to be robust among the 43 individual events. As such, they provide a remarkably coherent signal bearing the hallmarks of downstream development. Ninety six hours prior to the time of the mature Kona low (−96; hereafter, this convention will be used to indicate lead times), a NW–SE aligned dipole pattern in the anomalous PV (labeled 'A' in Figure 1) and the expected accompanying pattern in the meridional wind field are observed approximately 65 degrees of longitude upstream of the eventual mature Kona low center. The observed orientation of the relevant PV anomalies is consistent with a weakening of the wave guide in this region, a feature that has been noted in previous studies [*Otkin and Martin*, 2004a, 2004b]. During the ensuing 48 hours, the relevant features propagate eastward and the positive (negative) PV anomaly weakens (intensifies) considerably, while a new positive PV anomaly emerges downstream. These results are indicative of a downstream propagation of a wavepacket and an accompanying perturbation of kinetic energy.

[11] By −48, a large amplitude ridge/trough pattern centered approximately 20 degrees upstream is evident along the dynamical tropopause associated with the negative/positive PV anomaly couplet (labeled 'B' in Figure 1c). The observed intensification of the negative PV anomaly upstream of the formation region is itself integral to the formation of the PV streamer and, by inference, in the Kona low genesis. In effect, the anticyclonic circulation associated with the negative PV anomaly is of prime importance for the meridional stretching on its eastern flank that helps to create and enhance the downstream streamer. This process has been previously documented for a case of heavy Alpine precipitation [*Massacand et al.*, 2001].

[12] A further intriguing feature of the composite is the quasi-stationary low PV anomaly located directly upstream of the mature Kona low location at −96 and that is evident to a lesser degree until −24 (labeled 'C' in Figure 1). This composite feature suggests the presence of an atmospheric block [e.g., *Schwierz et al.*, 2004] in at least some individual Kona low events. A direct comparison of the Kona low events with the blocking climatology of *Croci-Maspoli et al.* [2007] shows this is indeed the case in 12 out of the 43 cases. In many of the additional cases, a block-like feature is present, although it falls short of meeting the fairly stringent criteria outlined by *Croci-Maspoli et al.* [2007].

[13] The presence of an upstream surface cyclone is evident as early as −72 and is observed to intensify over the subsequent 48 hours, reaching maximum intensity at −24 hours. An examination of the individual events confirms that, without exception, there is a surface cyclone located in the western or central Pacific upstream of the Kona low genesis region, although the exact location and intensity varies from case to case. This is a robust and previously un-reported feature of Kona low genesis. A subset of these surface cyclones, nearly 20 percent, are the direct result of the extratropical transition of a tropical cyclone (as diagnosed by the Joint Typhoon Warning Center).

[14] Two primary regions of composite 700 hPa diabatic heating (not shown) are identified: to the south and southeast of the upstream surface cyclone center and associated with the PV streamer/cut-off itself. The position of the former region of diabatic heating at −48 and −24 with respect to the upper-level trough/ridge pattern suggests that diabatic effects may play a significant role in amplifying the upper-level feature through the upper-level depletion of PV associated with diabatic processes. This facet of Kona low genesis will be looked at more closely via a case study analysis in the following section.

[15] The results of the composite analysis represent coherent, statistically significant anomalous features as far back as 96 hours prior to Kona low maturity. Furthermore, a multitude of dynamical processes (downstream development and atmospheric blocking) and physical processes (both adiabatic and diabatic) appear to be involved. The overall complexity evident in the composite analyses speaks to the difficulty of the forecast problem posed by PV streamer formation and Kona low genesis.

[16] The disturbance evolution presented herein exhibits a strong similarity to that found for cut-off lows over Northwest Africa that can spawn heavy precipitation events [*Knippertz and Martin*, 2005, 2007]: *Knippertz and Martin* [2007] identified the importance of both upstream and downstream PV ridges and diabatic processes associated with an upstream, intensifying surface cyclone in the formation of a PV streamer and cut-off low. This apparent similarity suggests the integral role of PV streamers in a subset of high impact, subtropical weather events is not geographically limited to the central Pacific.

4. Downstream Development: A Case Study

[17] The Kona low that occurred 24–28 February 1997 resulted in over four million dollars in damage in the Hawaiian Islands [*Morrison and Businger*, 2001]. It was associated with high winds, large hail, heavy rains and flooding. The synoptic structure and evolution of the Kona low itself has been examined in detail by *Morrison and Businger* [2001]. The event is briefly examined here to illustrate downstream development in an individual Kona low genesis event and to highlight the importance and to more closely examine the mechanism responsible for the upstream ridging that results in the formation of a PV streamer.

[18] The 250 hPa PV and meridional wind anomalies for the event are presented in Figure 2. As might be expected, the atmospheric state associated with an individual event is

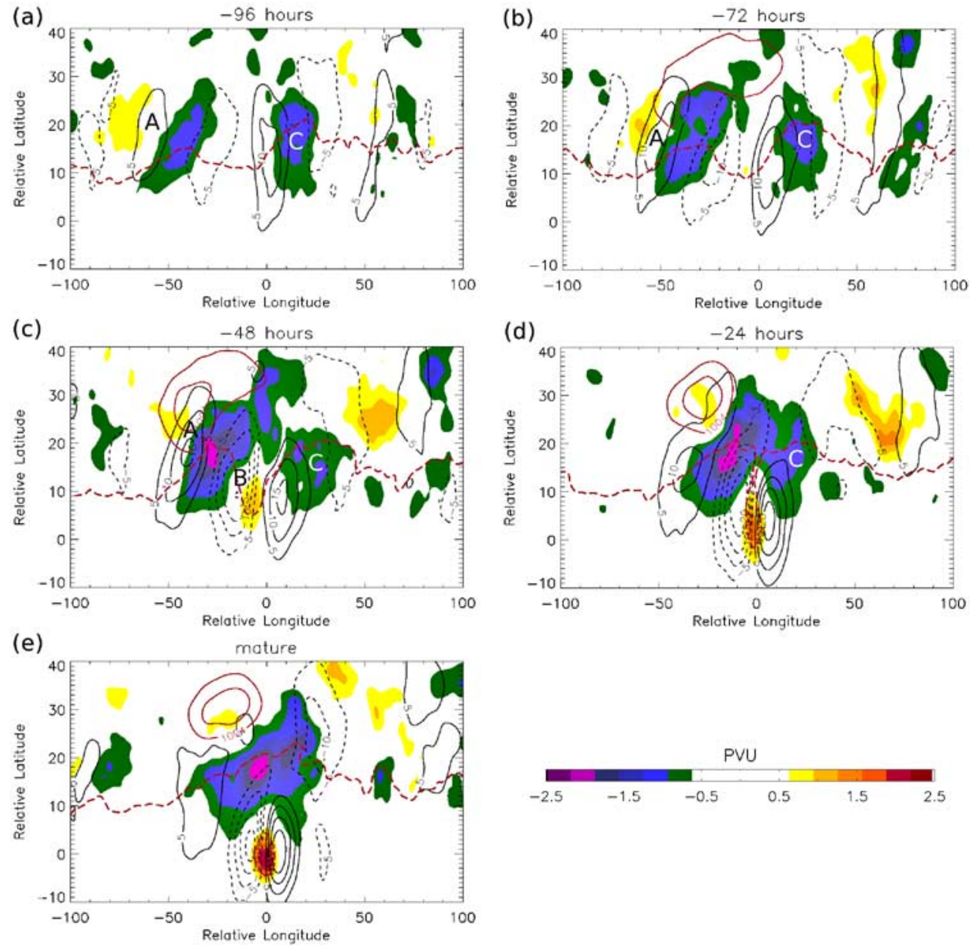

Figure 1. Composite analysis of 250 hPa potential vorticity (shading; PVU) and meridional wind (black contours; m/s; solid and dashed represent positive and negative values, respectively; contour interval of 5 m/s) anomalies, the 250 hPa 2 PVU contour (dashed gray) and select isobars of sea level pressure (solid gray; Pa) at times: (a) mature −96 hours, (b) mature −72 hours, (c) mature −48 hours, (d) mature −24 hours, and (e) mature. 'A', 'B' and 'C' mark features discussed in the text. The 1008, 1008/1004, and 1004/1000 hPa contours are provided in Figures 1b, 1c, and 1d/1e, respectively.

considerably more complex than that viewed in the composite framework. Nevertheless, the observed evolution of this destructive storm is qualitatively consistent with the composite analysis. Upstream of Hawaii, an undulation on the dynamic tropopause forms (Figure 2a) and amplifies as it propagates eastward (Figure 2b). Subsequently, strong ridging associated with an intensifying negative PV anomaly (labeled 'B' in Figure 2) spawns a downstream PV streamer and a cutoff positive PV anomaly (labeled 'C' in Figures 2c and 2d, respectively).

[19] Downstream development can be quantified via an analysis of the vertically integrated kinetic energy (KE) and energy flux vectors (Figure 3). At −72, two centers of KE (defined as locally-large values of vertically-averaged kinetic energy; labeled 'A' and 'B' in Figure 3) are identified in the western/central Pacific. They are associated with locally enhanced 250 hPa wind on both flanks of the central negative PV anomaly ('B') centered at 37N, 170E in Figure 2a.

[20] Energy flux vectors describe the direction of energy dispersion [*Orlanski and Sheldon*, 1995]. Specifically, the convergence of energy flux vectors leads to a positive local tendency in kinetic energy. During the 48 hours between −72 and −24, a downstream transfer of energy from center 'A' to 'B' is evident both in the changes in the respective magnitudes of the two KE centers and the structure of the energy flux vector field. While the observed changes in KE are, to first order, well described by the structure of the energy flux vector field, it should be noted that the baroclinic conversion (not shown) plays a non-negligible role: it helps to fortify KE center 'A', providing energy that can be subsequently transferred downstream. The downstream development in this case culminates with the formation of the PV streamer and cut-off low, the breaking wave precluding further downstream development.

[21] Also qualitatively consistent with the composite analysis, a large amplitude negative PV anomaly (identified as an atmospheric block, labeled 'D' in Figure 2) is located to the north and immediately downstream of the formation region. A previous wave breaking event, the remnants of which are visible at 140W at −72 (labeled 'A' in Figure 2a), may have played a role in sustaining blocking feature 'D'. Between −48 and −24, a strong deformation field forms

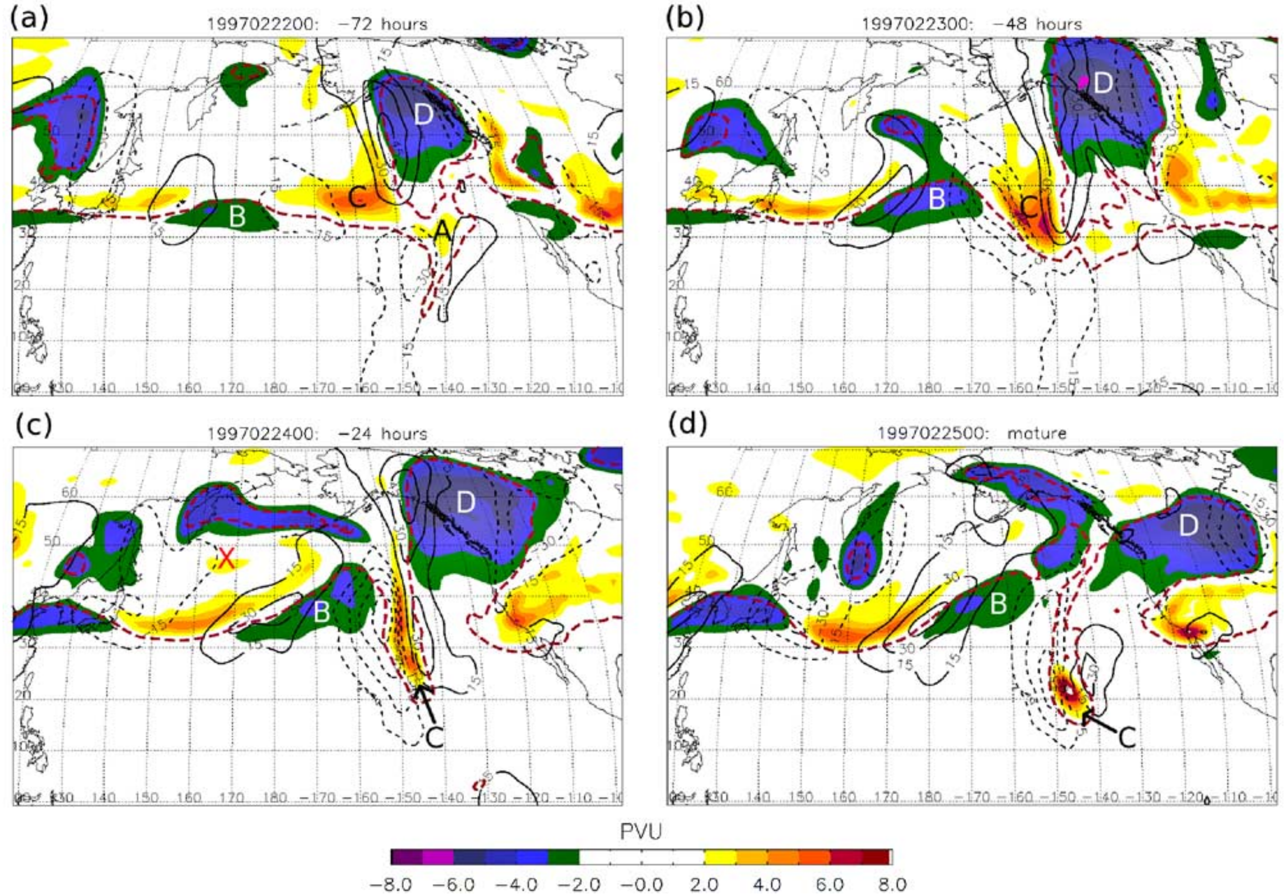

Figure 2. (a–d) Same as Figures 1b–1e, respectively, except for the 1997 Kona low. 'A', 'B', 'C', 'D', and 'X' mark features discussed in the text.

between blocking feature 'D' and the intensifying upstream negative PV anomaly ('B'). The deformation likely aids the zonal narrowing of the positive PV anomaly ('C') located between the two features. Contemporaneously, due to the more southerly position of the upstream negative PV anomaly, the enhanced northerly flow on the western flank of the incipient PV streamer helps the equatorward extension of this feature.

[22] In this scenario, the downstream propagation and amplification of the upstream low PV anomaly is integral to the formation of a PV streamer. To investigate the mechanisms responsible for the enhancement of the low PV anomaly, 36-hour backward trajectories from the region of low PV ('B') at −24 are calculated using the method of *Wernli and Davies* [1997]. Two coherent air streams with very different characteristics are identified: an upper-level stream of air that remains in the vicinity of the jet (comprising roughly 85 percent of all trajectories) and an ascending airstream originating in the subtropical boundary layer associated with the warm conveyor belt of an intense extratropical cyclone (SLP minimum of 958 hPa at −24; 'X' in Figure 2c). The former contributes to the negative PV anomaly through the adiabatic advection of low PV air into the region in question, whilst the latter results in a depletion of upper-level PV primarily at the apex of the ridge via diabatic processes. In this case, therefore, both adiabatic and diabatic processes play a significant role in strengthening the requisite low PV anomaly.

5. Discussion

[23] The composite analyses of 43 Kona low events and the specific example of the 1997 Kona low indicates downstream development is an important feature of, and dynamically important for, Kona low genesis. This deduction prompts two related questions. What makes Kona low genesis such a rarity? With the classification of *Caruso and Businger* [2006], Kona lows are relatively infrequent (43 cases in 22 years). Second, what are the necessary precursor conditions for subtropical cyclogenesis to occur in the central Pacific?

[24] Previous work related to these issues have focused on the structure of the jet in the central Pacific, the characteristics of the upper-level anomaly and the local conditions in the formation region. The present analysis suggests expanding this purview to incorporate studying processes occurring both far upstream and immediately downstream of the location of the upper-level cutoff. In effect, it might be necessary to assess the state of the atmosphere over a very broad swath of the Pacific basin to adequately predict PV streamer formation, highlighting the difficult medium-range forecast challenge posed by Kona low genesis.

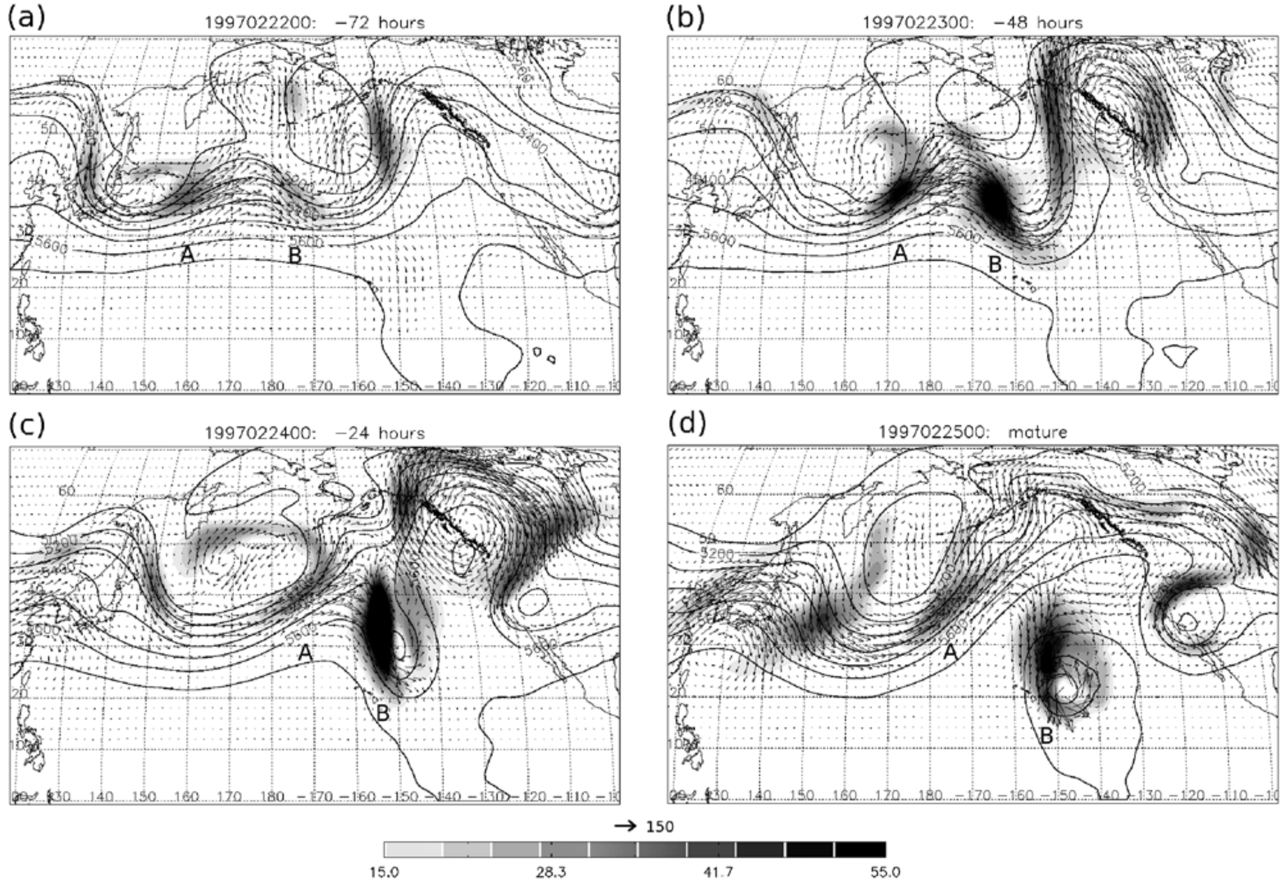

Figure 3. (a–d) Vertically averaged kinetic energy (shading; 10^5 J m^{-2}) and energy flux vectors (10^5 W m^{-1}; reference vector above colorbar) for the 1997 Kona low. 'A' and 'B' mark the longitude of the kinetic energy centers discussed in the text.

[25] This inference begs a number of pertinent questions:

[26] 1. Upstream surface cyclogenesis is a robust feature of the 43 Kona low events. Is there something fundamentally different from climatology in the strength and location of these precursor disturbances?

[27] 2. The composite analysis suggests and it was directly found to be true in the 1997 Kona low that diabatic effects associated with a warm conveyor belt are integral to the intensification of an upper-level negative PV anomaly: are diabatic processes of primary importance in most cases of Kona low genesis? If so, is it possible that environmental conditions in the lower-level subtropical atmosphere upstream of the Kona low genesis region are relevant to Kona low formation?

[28] 3. For the 43 cases presented here, approximately 20 percent were directly associated with extratropical transition events (ET). How often does an ET event result in Kona low genesis? Furthermore, does ET even need to be successfully completed? The divergent outflow and large amplitude diabatic processes associated with a decaying tropical cyclone can strongly influence the midlatitude jet even if there is no surface re-intensification in the extratropics.

[29] 4. A downstream atmospheric block, or a block-like feature, is present in a significant subset of Kona low events. A likely scenario for its possible role in Kona low genesis is outlined in the previous subsection. Is this scenario valid for all cases or is there significant case to case variability?

[30] These topics are the subject of ongoing analysis.

[31] A unique and timely opportunity for the further study of Kona lows exists within the framework of the upcoming Observing System Research and Predictability Experiment (THORPEX) Pacific Asian Regional Campaign (T-PARC), a multi-national effort scheduled for the second half of 2008. A core issue of T-PARC is to better understand the impact of cyclogenesis in the western Pacific on downstream predictability. Kona low genesis and predictability are intimately connected with this issue. It can therefore be hoped that T-PARC will provide a forum for discussion and a dataset uniquely suited to provide insight into these intriguing, yet presently unanswered, questions.

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