Intrusions into the Tropical Upper Troposphere: Three-Dimensional Structure and Accompanying Ozone and OLR Distributions

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(Manuscript received 13 May 2002, in final form 10 September 2002)

ABSTRACT

The evolution and structure of stratospheric intrusions into the upper troposphere (UT) over the northern tropical Pacific is examined in terms of both potential vorticity (PV) and ozone (O_3). Analysis of 20 years of NCEP-NCAR reanalysis PV shows that the intrusion events have remarkably similar evolution and structure at 350 K, with all events producing narrow tongues of high PV that have an almost north–south orientation and last around 3 days.Nearly all events extend up into the lower stratosphere, but only for a small percentage is there deep downward penetration. The intrusions explain a large amount of the observed variability in upper tropospheric O_3 above Hilo, Hawaii, with large values occurring when a tongue of high PV passes over Hilo and low values when Hilo is just upstream of a high-PV tongue. There is also an increase in total column ozone within the PV tongues, but for most intrusions the increase is relatively small. The relationship between deep convection, as diagnosed by satellite observations of outgoing longwave radiation (OLR), and intrusions is also examined. It is shown that transient convection and intrusions in the central and eastern northern Pacific nearly always occur together, with the convection at the leading edge of the PV tongue. This confirms the results of previous studies that have shown a close link between Rossby wave activity and transient convection, and supports the hypothesis that the ascent and reduced static stability due to anomalous PV in the UT initiates and supports the convection.

1. Introduction

A climatological feature of the upper troposphere during northern fall through spring is the existence of equatorial westerlies over the Pacific and Atlantic Oceans. These equatorial “westerly ducts” are important regions for extratropical–tropical interactions. Stationary linear Rossby waves propagate through westerlies, and cross-equatorial wave propagation is possible through the westerly ducts (e.g., Webster and Holton 1982; Hoskins and Ambrizzi 1993; Tomas and Webster 1994). Furthermore, if Rossby waves are of sufficiently large amplitude “wave breaking” can occur and tongues of high potential vorticity (PV) can intrude into the Tropics (e.g., Hsu et al. 1990; Kiladis and Weickmann 1992; Numaguti 1995; Waugh et al. 1994; Waugh and Polvani 2000). Waugh and Polvani (2000) formed a climatology of these “intrusions” events, and showed that the events occur predominantly within the westerly ducts. They further showed that there is large interannual variability in the occurrence of Pacific events, and that this variability is highly correlated with the phase of the El Niño–Southern Oscillation (ENSO), with fewer intrusion events in the warm phase (El Niño) when there are weaker upper troposphere (UT) equatorial westerlies in the Pacific. These subtropical wave breaking events may also influence the distribution of tracer constituents in the UT by mixing air of stratospheric origin, for example, high ozone and low water vapor, into the tropical UT (e.g., Scott et al. 2001). Furthermore, several studies have linked Rossby wave propagation into the tropical central and eastern Pacific with the occurrence of deep convection (e.g., Kiladis and Weickmann 1992; Kiladis 1998; Slingo 1998; Matthews and Kiladis 1999).

The above studies have addressed several different aspects of the Rossby wave breaking in the westerly ducts; however, there remain many outstanding issues. For example, the spatial structure and evolution of PV during events has not been examined in detail. Several case studies have been presented but there has been no examination of the climatological structure, and it is not known how different or similar events are. Furthermore, the vertical extent of the intrusions has not been examined. If intrusions extend down into the middle and lower troposphere they could have a large impact on the water vapor distribution, and activation of deep convection (e.g., Sherwood 1999; Yoneyama and Parsons 1999), while, if they extend into the lower stratosphere, then these events may be an important mechanism for the transport of air into the tropical stratosphere (Plumb 1996; Horinouchi et al. 2000).

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Although we expect the intrusions to have an impact on ozone, and other trace constituents, this has not been examined in detail. Most studies of tropopause folds and the relationship between ozone and PV near the tropopause have focused on middle latitudes, and there have only been a few case studies that have looked at ozone in subtropical events (Gouget et al. 1996; Folkins and Appenzeller 1996; Baray et al. 1998, 2000; Scott et al. 2001).

Previous studies have shown a strong relationship between Rossby wave activity propagating into the tropical Pacific and deep convection, and have presented examples where the convection occurs ahead of an intruding tongue of high PV. However, the role (if any) of wave breaking and formation of “anomalous” tongues of PV in initiating deep convection is not known. For example, it is possible that some of the Rossby wave activity associated with the convection may not produce wave breaking and intrusions. Also, the magnitude and structure of the anomalous PV produced during an event may have a large impact on the upward motion and convection.

Here, we address the above issues. We extend the analysis of Waugh and Polvani (2000), (hereafter WP2000) and examine the spatial structure of the intrusions over the northern Pacific Ocean in terms of both PV and ozone \((O_3)\), and also the relationship of intrusions with transient tropical convection as diagnosed by outgoing longwave radiation (OLR) measurements. In the next section we describe the various datasets used in our analysis. Example intrusion events that illustrate the three-dimensional PV structure of an intrusion, the associated changes in convection and ozone, and the dependence on source of meteorological data are presented in section 3. The climatological PV structure is examined in section 4, while the accompanying OLR field is examined in section 5. The vertical distribution of ozone at Hilo, Hawaii (Oltmans et al. 1996) and spatial distribution of total column ozone, as observed by the Total Ozone Mapping Spectrometer (TOMS), during intrusion events are examined in section 6. Concluding remarks are in section 7.

2. Data

We use potential vorticity calculated from National Center for Environmental–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data (Kalnay et al. 1996) to examine the structure of the intrusions. These data have 2.5° latitude by 2.5° longitude resolution and are available 6-hourly. In our analysis we focus on the PV distribution on isotropic surfaces between 330 K (=400 hPa in the Tropics) to 410 K (=80 hPa), and use 1200 UTC data from 1980 to 1999 (except for the analysis of Hilo ozone, where we use data at 1800 UTC which is closer to the typical launch time of the sondes).

These data are the same as used by WP2000 to form their climatology of the occurrence of intrusions, and we use the events defined in the WP2000 climatology to examine the mean structure of the intrusions. WP2000 defined their climatology by first identifying the occurrence of high PV \(\geq 2\) potential vorticity units (PVU); 1 PVU = \(10^{-6} K s^2 kg^{-1}\) at 10°N or 10°S. Then occurrences within 10° longitude or within 6 days were grouped into single intrusion events. Below, the middle day when PV at 10°N or 10°S exceeded the critical value is defined as “day 0” of the intrusion event (and “day −2” corresponds to 2 days before this day).

As there are limited observations over the tropical oceans there is some concern that features in the meteorological analyses may be dependent on the model used in the data assimilation procedure. To examine this issue we have compared the PV from different meteorological analyses for several events. Specifically we compare PV from the NCEP–NCAR reanalyses with that from the Met Office (UKMO) Upper Atmosphere Research Satellite (UARS) assimilation (Swinbank and O’Neill 1994) and the National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC) stratospheric data assimilation system (Schubert et al. 1993). The UKMO and GSFC systems use different numerical models and assimilation techniques, and have different resolutions (2.5° latitude by 3.75° longitude for UKMO data and 2° latitude by 2.5° longitude for GSFC data).

Another check on the reality of features in the analyzed PV is comparisons with \(O_3\) observations. A high correlation between PV and \(O_3\) is expected in the upper troposphere and lower stratosphere, and similar features should be seen in PV and \(O_3\) fields, that is, high \(O_3\) when there is high PV. Unfortunately, three-dimensional \(O_3\) data are not available for the region of interest. However, near-global measurements of the total column ozone are made by the TOMS satellite instruments (for more information see the Web site at http://toms.gsfc.nasa.gov). Three different TOMS instruments were operational at different periods during the 20 yr of interest. In our analysis we use total ozone data from Nimbus-7 (1 January 1980 to 6 May 1993), Meteor-3 (7 May 1993 to 24 November 1994), and Earth Probe TOMS (25 July 1996 to 31 December 1999). There is no TOMS data between 24 November 1994 and 25 July 1996. The TOMS data used has 1° latitude by 1.25° longitude resolution.

It is also possible to examine the vertical structure of ozone using measurements made by the NOAA Climate Monitoring and Diagnostics Laboratory (CMDL) at Hilo, Hawaii (19°N, 205°E; Oltmans et al. 1996). This is the only station in the northern subtropical Pacific with regular \(O_3\) measurements, with approximately weekly measurements since September 1982. Also, Hilo is located within the region where intrusions into the Tropics most frequently occur, and intrusions of high PV often pass over Hilo. In the analysis below we focus on Hilo data for the extended winter period, November

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*Note: The document appears to be a scientific paper discussing atmospheric and ozone studies, focusing on intrusion events and their impacts on ozone and PV. It references various datasets and models used to study these phenomena, and includes references to other studies and methodologies.*
through March (when PV intrusions generally occur), and use O\textsubscript{3} data from 17 winters (1982/83–1998/1999). The O\textsubscript{3} data used in this analysis has been averaged vertically into regular 0.5-km bins (and were kindly provided by Jennifer Logan).

The occurrence of convection near the intrusions is examined using outgoing longwave radiation as a proxy for tropical convection. We use the NOAA spatially and temporally interpolated OLR (Liebmann and Smith 1996), which were obtained from the NOAA–Cooperative Institute for Research in Environmental Sciences (CIRES) Climate Diagnostics Center (CDC; information available online at http://www.cdc.noaa.gov/). These data are available daily and on the same horizontal grid as the NCEP–NCAR reanalysis data, and we use the same 20-yr period as the PV data (1980–1999).

3. Illustrative examples

Before considering the climatological structure of the intrusions we first consider two illustrative examples. The first is an intrusion event that occurred over the northern Pacific in the middle of January 1987. This event is actually not counted in the WP2000 climatology as the PV at 10°N never exceeds 2 PVU during the event. However, the occurrence of tropical convection and relationship with meteorological fields during this event was examined by Kiladis and Weickmann (1992) and ozone measurements from Hilo were made on January 15 when the high-PV tongue was overhead. The detailed analysis of Kiladis and Weickmann (1992) and the availability of ozone data means that this event can be used not only to illustrate the PV structure but also the connection with convection and ozone.

Figure 1 shows the evolution of the PV on the 350-K surface and (low) OLR over the northern tropical Pacific between 13 and 18 January 1987. Contour interval for PV is 1 PVU, while shaded region shows OLR (south of 30°N) less than 180 W m\(^{-2}\). Solid circle is Hilo, Hawaii.
almost north–south orientation (there is only a slight SW–NE tilt). Over the next two days the tongue decayed, and the whole lifecycle (amplification and decay) of the tongue lasted around 6 days. As shown below, the above sequence of events is typical of the intrusions examined, and the above features can be seen in PV maps for other events, for example, figures in Hsu et al. (1990), Tomas and Webster (1994), Numaguti (1995), and WP2000.

The maps in Fig. 1 also show changes in the OLR during this period. In particular, a region of low OLR, and presumably deep convection, occurred just ahead of the high-PV tongue. The region of low subtropical OLR appears around 15 January and lasts around 4 days. As mentioned above, Kiladis and Weickmann (1992) performed a detailed analysis of the meteorology and OLR during this event. They showed that the region of low OLR ahead of the tongue is collocated with a region of upward motion at 500 hPa, and argued that this ascent (and reduced static stability) could be attributed to the anomalous PV within the intruded tongue. The link between low OLR and intrusions is examined further in section 5.

The vertical structure of the intrusion on 15 January is shown in Fig. 2. Figures 2a–c show that a tongue of high PV intrudes into the Tropics at all levels from 330 K (middle troposphere) to 410 K (lower stratosphere). The width of the tongue increases slightly with height, but the location and NW–SE tilt varies little between 330 and 410 K. The anomalous nature of the PV in the tongue can be seen by comparing the vertical profile of PV over Hilo (solid circle in Figs. 2a–d) on 15 January with the climatological winter values, see Fig. 2e (the shaded region shows the climatological mean plus and minus the standard deviation of daily values). The values on 15 January are around or larger than the climatological mean plus one standard deviation from 700 hPa to over 70 hPa, with very large values between 300 and 200 hPa (340–350 K).

The impact of this intrusion event on the ozone dis-
distribution is shown in Figs. 2d and 2f, which show total column ozone from TOMS and the vertical profile of ozone above Hilo, respectively. There is a strong signature in the both the horizontal and vertical distributions of ozone. The ozone above Hilo is larger than the mean throughout the troposphere, with anomalously large values from below 200 hPa to above 100 hPa, while the total column ozone in the tongue near Hilo is over 300 Dobson Units (DU; compared with the climatological mean January value of around 255 DU). The similarities in the structures in the Oz and PV fields, and in particular the near north–south orientation in both the tongues of total column ozone and PV, gives us confidence in the reality of the analyzed PV.

As a further check on the PV from the NCEP–NCAR reanalyses we have compared this PV with that from the UKMO and GSFC meteorological analyses for several events. (These data are not available for the above 1987 event.) Figure 3 compares the PV at 350 K from the three analyses for an event that occurred on 16 January 1997 (in each plot the bold contour is the PV = 2 PVU contour from the NCEP–NCAR reanalyses). There is excellent agreement, with all analyses showing a narrow tongue of high PV with almost north–south orientation that reaches 10°N at 125°W, as well as a northward extension of the PV = 4 PVU contour west of the tongue and a local maximum around 35°N, 115°W. Figure 3d shows the TOMS total ozone for the same day, and there is again good agreement between features in the total ozone and those in the PV; that is, there is a tongue of high ozone with similar structure and location as the PV tongue. Other comparisons (not shown) also show excellent agreement in the structure of PV tongues in the different analyses, and the structure of the tongues are not dependent on the source of the meteorological analyses.

The above examples show that intrusion events can produce tongues of high PV and ozone, which extend from the middle troposphere to lower stratosphere, and simultaneously deep convection (as diagnosed by low OLR) can occur ahead of the high-PV/ozone tongue. In the following sections we examine whether these are climatological features of the intrusion events.

4. Potential vorticity

We now examine the climatological PV structure of the intrusion events in the North Pacific region. All days when there is an intrusion, as defined by WP2000 (see section 2), in the North Pacific are grouped together,
and the mean PV field ("composite mean" PV) is calculated. The temporal evolution of the composite mean PV is examined by repeating this analysis for days −3 to 3, that is, 3 days prior to and 3 days after the peak of the intrusion. Although we formed composites for just North Pacific events there is still variation in the longitude of the high-PV tongues, and the averaging of all events removed a lot of the structure. We therefore formed composites in which the PV fields were shifted in longitude so that the PV tongue at day 0 occurred at the same notional longitude (140°W); that is, the PV fields were shifted so that events are "in phase." All results presented below are from these "phase-shifted" composites.

Figure 4 shows maps of 350-K PV for the phase-shifted composite of events in the North Pacific, for day −3 to day 2. Also shown is the composite OLR, which will be discussed in the next section. The evolution and structure of the composite PV is very similar to that of the PV in the individual event shown in Fig. 1. A disturbance to PV contours near the tropopause propagates eastward and amplifies, producing a tongue of high PV that extends south of 10°N. As in the January 1987 event the high-PV tongue in the composite mean has almost north–south orientation and lasts around 3 days. The gradients of PV and maximum PV in the tongue are weaker than in the individual event shown in Fig. 1. However, considering the composite mean is the average of 103 events, the similarity between the composite mean and individual events suggests that the vast majority of the intrusions have very similar evolution and structure. The variability between events is examined below.

The mean vertical structure of the intrusions is examined by forming composite PV fields on several other isentropic surfaces, for the same days used to form the 350 K composites. Figure 5 shows the composite PV at day 0 for levels between 330 to 410 K. At all levels there is a tongue of high PV reaching to lower latitudes at roughly the same longitude. The strength of the
tongue weakens as you move up or down from 350–370 K, and is relatively weak at the lowest and highest levels shown. For example, at 350 K the PV contours that are normally around 30°N (PV = 2 PVU) reach as far south as 10°N, whereas at 330 and 410 K the southward movement of contours around 30°N is only a few degrees latitude.

To examine the variability between different individual events we examine the distribution at different locations of the PV at day 0. Figure 6 shows the distributions of PV at 330, 350, and 410 K for the reference longitude and three different latitudes (10°N, 15°N, and 20°N), see crosses in Fig. 5.

Consider first the distributions at 350 K (middle column in Fig. 6). At 10°N, all the PV values are equal to or greater than 2 PVU (as required to be included in the WP2000 climatology), and the distribution is very narrow with PV between 2 and 2.5 PVU in all but a few cases. More symmetric distributions are found at more northern points, and also east and west of the reference longitude (not shown). However, the spread at 15°N is still relatively small. This indicates that there are rather small variations in PV between different intrusion events, that is, intrusions have very similar spatial structure. Note that the mean value at 15°N is actually greater than at 20°N. This is because of the NE–SW tilt of the intrusions (see Fig. 5), and at 20°N the largest PV values are east of the reference longitude (the mean PV 5° east of the reference longitude is larger by 1 PVU).

The distributions at 410 K (right column in Fig. 6) are also symmetric with a relatively small spread about the mean value. The mean values increase from around 5 to 8 PVU from 10°N to 20°N [compared to the December–January–February (DJF) mean values of 3 to 6 PVU for 10° to 20°N at 220°E], while the standard deviation is around 1.5 PVU for all latitudes. This shows there are only small variations in 410-K PV between different events, and that most events have higher than normal PV at 410 K.

At 330 K (left column in Fig. 6), the distributions are somewhat different. In nearly all cases the PV is less than 1 PVU, and only in a few cases is the PV greater than 1.5 PVU at, or south of, 20°N. This indicates that in only a few of the intrusions is there a deep downward signal in the PV. In other words, the strong signal in 330-K PV seen in the January 1987 event (Fig. 2) is not seen in most intrusion events. Note that even though there is not a strong signal in the analyzed PV there may be finer-scale features, as seen in high-resolution trajectory calculations (e.g., Scott et al. 2001), that are not resolved in the analyzed PV. Visual inspection of the PV for events with strong signature at 330 K (i.e., PV ≥ 2 PVU at 20°N) shows that for these events the tongue at 350 K is narrower, with stronger gradients, and more north–south orientation than the tongue in the composite mean field.

Examination of phase-shifted composites for events in the South Pacific and the North and South Atlantic regions show very similar features to the North Pacific region (not shown). The climatological mean PV fields show a well defined high-PV tongue with almost north–
south orientation, and there is only small event-to-event variability. However, the Southern Hemisphere events are noticeably weaker than the Northern Hemisphere events.

5. Outgoing longwave radiation

As discussed in the introduction, several studies have shown that there is a link between Rossby waves propagating into the Tropics and transient deep convection in the eastern tropical Pacific (e.g., Kiladis and Weickmann 1992; Kiladis 1998; Slingo 1998; Matthews and Kiladis 1999). Kiladis and Weickmann (1992) examined the January 1987 event discussed in section 3 and showed that convection, as diagnosed by OLR, occurred ahead of an intruding tongue of high PV. They further suggested that the ascent and reduced static stability ahead the PV tongue initiated/supported the convection (see also Kiladis 1998). However, it is not clear whether all convective events are linked with tongues of PV, and whether there is convection ahead of all tongues of PV. We examine these issues by examining the OLR for the intrusion events examined in the previous section.

We form phase-shifted composites of the OLR in exactly the same manner as the PV composites in the last section. Figure 4 shows the composite mean OLR for North Pacific intrusion events, with values less than 240 W m\(^{-2}\) and south of 30\(^\circ\)N shaded. As in Fig. 1, the region of low OLR occurs at the leading edge of the tongue of high PV, and appears around the peak of the intrusion event. This signature of low OLR in the composite fields supports the hypothesis of Kiladis and Weickmann (1992) and Kiladis (1998) that the ascent and reduced static stability ahead the PV tongue will initiate/support convection.

The value in the composite OLR is not as low as in the January 1987 example shown in Fig. 1 (the minimum value in the composite is around 220 W m\(^{-2}\) compared to less than 160 W m\(^{-2}\) on 15 January 1987). However, examination of individual events shows that there is generally low OLR around the leading edge of the tongue but that there is a lot of variability in the exact location of the low OLR. Because of this spatial variability the minimum value in the composite mean is significantly higher than the minimum in individual events.
To examine the variations in low OLR we determine, for each intrusion event, the minimum OLR in the vicinity of the PV tongue. Figure 7 shows the distributions of minimum OLR and the longitude of this minimum relative to the reference longitude. These plots show that nearly all events have a region of OLR much lower than in the composite mean (70% of the events have a region of OLR less than $170 \text{ W m}^{-2}$), and that the location of low OLR is nearly always ahead of the tongue (longitude is around $10^\circ$ to $12.5^\circ$ ahead of the reference point). We have repeated this analysis using the average OLR in $5^\circ$ latitude by longitude boxes, and the distributions of minimum OLR and location are similar.

The above indicates that when there is an intrusion (tongue) of high PV there is nearly always low OLR, and hence deep convection. But does similar convection occur when there are no such PV events? To examine this we define events where the OLR is anomalously low (“low-OLR” events), and form phase-shifted composites of both the OLR and PV for these events.

To define low-OLR events we first examine the variability of OLR in the eastern tropical Pacific. Figure 8 shows a longitude–time plot of OLR at $15^\circ$N from 1 December 1986 to 28 February 1987, with values less than $210 \text{ W m}^{-2}$ shaded. This shows that there were several brief periods during this winter when there was very low OLR (e.g., below $210 \text{ W m}^{-2}$) and that these occurred between $100^\circ$ and $150^\circ$W. Note that one of these periods (15–17 January) is associated with the intrusion event shown in Fig. 1. Plots for other years show similar temporal variability, with brief periods with OLR much lower than the winter mean values [see also Fig. 6 of Matthews and Kiladis (1999) for OLR time series at $130^\circ$–$140^\circ$W for several winters]. For our analysis we define “OLR events” as periods when the average OLR within the region of interest is less than $210 \text{ W m}^{-2}$ (as in the PV intrusion climatology, consecutive days are grouped together as one single event). In the analysis below we focus on OLR events in the region $10^\circ$–$20^\circ$N and $130^\circ$–$140^\circ$W. For December 1986 to February 1987 there were six events in the region (see dashed lines in Fig. 8), but there is large interannual variability in the number of events, with the number varying between 0 and 10 (with fewer events during the warm phase of ENSO). See Matthews and Kiladis (1999) for further discussion on the interannual variability of convection in the eastern tropical Pacific.

Using the above criteria applied to 20 yr of DJF data we form composite mean OLR and PV fields as in section 3, except here, the events are defined on low OLR rather than high PV. Figure 9 shows maps of the composite OLR and 350-K PV for days $-3$ to 2 of the low-OLR events in the region $10^\circ$–$20^\circ$N, $130^\circ$–$140^\circ$W. (Similar maps for composites of low-OLR events in different, nearby, regions show very similar features). These maps show a similar evolution of PV and OLR as the composite maps for PV events (Fig. 4). A trough in the PV...
contours forms to the northwest of the reference region (with low OLR) around 2 to 3 days before the reference data; the minimum OLR occurs around the same time as the maximum perturbation to the PV contours; and the low OLR is ahead (east) of the PV trough. As might be expected, the minimum in OLR is better defined (lower) and the tongue of high PV less defined (weaker) in the composite based on OLR events than the composites for the PV events. However, both composites indicate a strong connection between high PV at 350 K and low OLR.

As for the case of the composite mean OLR for the high-PV events, the structure and magnitude of the composite mean PV for low-OLR events is reduced because of the averaging over a large number of events. Analysis of the distribution of maximum PV around the reference region shows that in nearly all of the low-OLR events there is a tongue of high PV west (upstream) of the region of low-OLR, and, consistent with the analysis of OLR associated with PV events, the mean shift is around 10° longitude. Note that, in the majority of these tongues the PV = 2 PVU contour does not reach as far south 10°N, and hence these days are not included in the WP2000 intrusion climatology (and the above analysis of PV events). However, this analysis still shows that low OLR, in the northeastern tropical Pacific, usually occurs in the vicinity of a tongue of anomalously high PV in the UT.

6. Ozone

As discussed in section 2, the impact of intrusions on ozone is examined using ozonesonde measurements at Hilo (19°N, 205°E) and total ozone from the TOMS satellite instrument. We first examine the changes in the vertical structure of ozone over Hilo, and then the spatial and temporal variations in total column ozone.

a. Hilo ozonesondes

Measurements of the vertical profile of ozone above Hilo have been made approximately once per week since

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**Fig. 9.** Maps of phase-shifted composite mean 350-K PV (thick contours; contour interval is 1 PVU) and OLR (shaded regions) for days −3 to +2 of OLR low events in 10°–20°N, 220°–230°E. Only OLR south of 30°N and less than 230 W m⁻² is shown.
September 1982, see Oltmans et al. (1996) and Logan (1999) for discussion of climatological features. We consider here measurements during the extended winter period November through March. We first consider the 1986/87 winter to illustrate the day-to-day variability, and then examine data from 17 winters (1982/83–1998/1999).

Figure 10 shows the temporal variation of the PV at 350 K over Hilo for the 1986/87 winter (the PV is shown once per day at 1800 UTC the approximate time of the ozonesonde releases). The vertical dotted lines show the dates when ozone measurements are available, and the symbols the observed O3 at 200 hPa. This plot shows that there can be large day-to-day variations in the PV over Hilo. For this winter, the average PV is around 0.5 PVU, but sporadically there are large, rapid increases, with PV exceeding 3 PVU on several occasions.

Visual inspection of PV maps shows that the large, rapid increases (as well as some of the very low values) in Fig. 10 are generally associated with the passage of a tongue of high PV over Hilo (i.e., intrusion events). An example of one such intrusion in mid-January was discussed earlier in section 3 (see Fig. 1). The PV tongue...
generated during this event passes over Hilo on 14 and 15 January 1987, and there a dramatic increase in the PV at 350 K during these days. Further illustration of the connection of variability in PV with intrusion events is seen in Fig. 11 which shows maps of PV at 350 K for the 6 days between 7 January and 13 February 1987 when ozone measurements were made from Hilo. During this period a series of Rossby waves propagated along the tropopause and through the region shown, and several of these amplified and produced tongues of high PV within central-eastern Pacific, for example, 15, 22, and 27 January. Comparing Figs. 11 and 10, it can be seen that the large variations in PV over Hilo are related to the position of these tongues relative to Hilo, that is, high values when tongues over Hilo on 15, 22, and 27 January. Note also that there is low PV over Hilo on 13 February when a developing tongue of high PV is just upstream of Hilo.

The above analysis shows that intrusion events frequently pass over Hilo and have a strong influence on the variability of PV. We now examine the impact of these intrusions on O₃ over Hilo. Figure 12 shows vertical profiles of the O₃ (solid curves) and PV (dashed curves) for the days shown in Fig. 11. As expected from Figs. 10 and 11, there is large variability in the PV in the UT/lower stratosphere (LS) with high values on some days (15, 22, and 27 January) and low values on others (13 February). There is similar variability in the O₃ profiles (both vertical and day-to-day), and there is a reasonable correlation between O₃ and PV (see below).
Fig. 13. Interannual variations in (a) winter mean PV at 350 K (solid) and \( O_3 \) at 200 mb (dashed) over Hilo, and (b) high-PV events over Hilo (solid) and intrusion events from WP2000 (dashed). Note “1985” on x axis, corresponds to winter 1984/85.

The above analysis shows that the passage of intrusion events over Hilo caused significant changes in both PV and \( O_3 \) in the UT/LS during January–February 1987. We now examine whether this holds over the whole data record. Plots similar to Fig. 10 for other winters show that there is large interannual variability in the mean winter value and the occurrence of very high PV over Hilo. This is shown by the solid curves in Fig. 13, which show (a) the winter mean PV at 350 K for days when \( O_3 \) data is available (the mean for all winter days is very similar) and (b) the number of events per winter with PV greater than 3 PVU (visual inspection of PV maps for these days shows that on nearly all days a tongue of high-PV was over Hilo), for each winter between 1982/83 and 1998/99. Both quantities have similar, large interannual variability, with low values during El Niño years (e.g., 1982/83 and 1997/98) and high values during El Niña years (e.g., 1988/89 and 1998/99). This interannual variability is similar to that of the intrusion climatology of WP2000 (see dashed curve in Fig. 13b), which further confirms the link between PV over Hilo and intrusion events.

Also shown in Fig. 13a are the winter mean values of \( O_3 \) at 200 hPa (approximately 350 K). (Note that there are not enough \( O_3 \) data to look at the statistics of events with high \( O_3 \) in the UT over Hilo.) The year-to-year variations in mean \( O_3 \) are very similar to the mean PV at 350 K, again showing low (high) values during warm (cold) phases of ENSO. The similarity of ozone and PV over Hilo can also be seen by comparing the profiles of climatological ozone and PV in Fig. 2.

The \( O_3 \)–PV relationship is further elucidated in Fig. 14, which shows scatterplots of \( O_3 \) versus PV at 250, 200, 150, and 100 hPa. At all four levels, higher \( O_3 \) is generally associated with high PV. The relationship is tighter at higher levels, with correlation coefficients equaling 0.57, 0.60, 0.72, and 0.73 on the 250- to 100-hPa levels. Note also that at all levels both the PV and \( O_3 \) distributions are skewed, with relatively rare occurrences of large values. The relationship is, however, not perfect, and there are some days with high PV but low \( O_3 \) and other days with low PV but high \( O_3 \).

The above analysis shows that there is large variability in \( O_3 \) in UT/LS over Hilo, and that the variations are well correlated with variations in the analyzed PV. Large values of \( O_3 \) (and PV) above the mean winter values are associated with intrusion events, and the occurrence of a tongue of high PV over Hilo. Also, very low values of \( O_3 \) can be associated with intrusion events: the air ahead and behind the high-PV tongues can come from equatorial regions, and have low ozone (e.g., 13 February 1987).

b. TOMS

The ozonesonde data provides high vertical resolution, but has limited temporal resolution and are available from only a few locations. It is therefore not possible to examine the daily variability of ozone or its horizontal structure from these data. However, information on daily and spatial structure of total ozone is available from TOMS (and other satellite) instruments.

We form phase-shifted composites of TOMS total ozone for days in the WP2000 intrusion climatology in the same manner as the PV and OLR composites discussed above. Figure 15 shows the phase-shifted composite mean total ozone for days −3 to 2 of North Pacific events (also shown is the composite mean PV = 2 PVU contour at 350 K). There is some signature in the total ozone composite (i.e., southward undulation of the 260 and 270 DU contours on days −1 and 0), but it is weak. Although the weak signal in total ozone could be due to averaging between events with a strong signal but differing spatial structure, visual inspection of total ozone maps shows that most intrusion events have only a weak signal in total ozone.

Although most events have a weak signal, the analysis
of the 15 January 1987 event (Fig. 2) showed a strong signature in total ozone can occur in individual events (with total ozone as large as 300 DU at 20°N). One difference between the 15 January 1987 event and most intrusion events is the deep downward extent of this event (i.e., as discussed in section 4 most events donot have a strong PV signal at 330 K). This suggests that a large change in total ozone may occur only in “deep” intrusion events with large PV at 330 K. This is supported by examination of the total ozone for the events with a strong signature in PV at 330 K (PV $\geq 2$ PVU at 20°N) which shows a tongue of high total ozone for each event (not shown).

7. Concluding remarks

The analysis of 20 years of NCEP–NCAR potential vorticity (PV) data shows that intrusion events over the northern tropical Pacific have remarkably similar evolution and structure between 340 and 370 K, with all events producing narrow tongues of high PV that have an almost north–south orientation and last 2 to 3 days. This can be contrasted with tropopause folds occurring in middle latitudes where there is large variability between events and the tongues of high PV are seldom aligned north to south. The reason why the subtropical intrusions have near north–south alignment is unclear, but may be related to the very weak meridional gradients in the zonal wind within the westerly ducts.

The intrusions can extend from the middle troposphere (330 K) to lower stratosphere (410 K). The upward extension into lower stratosphere is a robust feature and occurs in the vast majority of events, but deep downward penetration occurs only in a small percentage of the events. The extension of the events into the lower stratosphere may play an important role in determining the chemical composition in the tropical lower stratosphere. Analysis of trace gas observations indicate that, while there is a subtropical barrier to transport into the tropical stratosphere, it is not a perfect barrier and there is some mixing into the Tropics (e.g., Avallone and Prather 1996; Hall and Waugh 1997; Minschwaner et al. 1996; Volk et al. 1996). The intrusion events examined here appear to be one processes by which this transport occurs [see Horinouchi et al. (2000) for ex-
amination of this stratospheric transport in a general circulation model].

The analysis of O₃ measurements above Hilo shows that there is large variability in O₃ in the UT/LS, and that much of this variability is associated with intrusion events. Large values of O₃ occur when a tongue of high PV passes over Hilo, while very low values of O₃ occur when Hilo is upstream of a high-PV tongues and air is advected north from equatorial regions. This strong connection means that the interannual variability in the occurrence of intrusions (see WP2000) is a major factor in determining the interannual variability of UT ozone in the subtropical northern Pacific. Whether this is the case for other subtropical regions needs to be examined.

Analysis of the relationship between OLR (as a proxy for deep convection) and intrusions shows that transient convection and tongues of high PV in the UT nearly always occur together. This is consistent with the previous studies that have shown a close link between Rossby wave activity and transient convection (e.g., Kiladis and Weickmann 1992; Kiladis 1998; Slingo 1998; Matthews and Kiladis 1999). It further shows that the relevant Rossby waves are of large amplitude and produce “anomalous” tongues of PV. This tight connection between convection and tongues of PV, with the convection at the leading edge of the PV tongue, adds support to the hypothesis of Kiladis and Weickmann (1992) that the anomalous PV within the intruded tongue produces a region of ascent and reduced static stability that initiates the convection.

Although the analysis presented here has provided useful information of the structure of PV, O₃, and OLR during intrusion events, there are still several areas that need further investigation. The analysis performed here has confirmed that close link between intrusions and deep convection, but it does not address “cause and effect.” We are currently examining this using PV inversion (e.g., Davis 1992; Thorpe 1997) to determine the flow attributable to the PV tongue. The connection between midlatitude tropopause folds and convection is well known, and Griffiths et al. (2000) used PV attribution to examine the dynamical linkage in this case. It will be interesting to compare the induced flow in the subtropical events discussed here with that in midlatitude tropopause folds.

Also, our analysis has shown a link between the PV and O₃ distributions during intrusions but has not addressed the issue of the amount of irreversible transport.
of $O_3$ caused by the intrusion events. The lack of high-resolution three-dimensional data means that this issue will need to be examined using high-resolution models (e.g., Scott et al. 2001; Scott and Cammas 2002), in combination with available data. Also the impact of intrusion events on other trace constituents—for example, water vapor—needs to be examined. As the frequency of the intrusions varies with the phase of ENSO, it is possible that the intrusions play a role in the observed ENSO-related variations in UT humidity (e.g., Newell et al. 1997; Bates et al. 2001).

It is interesting to note that there may be some coupling between the convection and irreversible transport of trace constituents. The diabatic heating associated with the convection may play a role in the weakening of the PV anomaly [as noted by Kiladis (1998)], and the mixing of stratospheric and tropospheric air. So it is possible that the PV tongue may induce convection that leads to its own destruction and mixing of different air masses. Therefore, further investigations of transport and convection connected with intrusion events should be coupled together.

Acknowledgments. We thank Peter Hess, George Kiladis, Jennifer Logan, Sam Oltmans, Richard Scott, and Adam Sobel for helpful discussions and comments on earlier versions of the manuscript. We also thank Jennifer Logan for providing the binned Hilo $O_3$ data, and Paul Newman for the NCEP–NCAR analyses. The interpolated OLR data was obtained from the NOAA–CRES Climate Diagnostics Center (available online at http://www.cdc.noaa.gov/), and the TOMS data from GSFC (available online at http://toms.gsfc.nasa.gov/). This work was supported by NSF Grant ATM-009471.

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