Low-level transpacific transport

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[1] The role of low-level transpacific paths in bringing east Asian air to the North American west coast surface is determined using conditional transit-time distributions. These distributions are computed with the MATCH transport model driven by NCEP reanalysis data. Transpacific paths that lie entirely below ~2.2 km contribute negligibly to the west coast column burden of east Asian air. However, during summer such paths account for about half of the climatological west coast surface mixing ratio of east Asian air with transit times of less than ~3 weeks. Summertime transport is characterized by distinct upper and lower level transport modes, which form by convective injection and boundary layer outflow into a summertime marine troposphere of high stability and weak baroclinicity. During the other seasons the climatological east Asian air plume organizes into distinct midlatitude and subtropical parts, particularly evident during spring and fall. The midlatitude plume is characterized by mixing along sloping isentropes, which transports low-level air aloft over the western Pacific and brings midtropospheric air to the surface over the eastern Pacific. The subtropical part of the plume is formed by convectively injected air. Lagged, weighted composites show that summertime surface events are characterized by strong low-level Asian outflow, while for the other seasons surface events are associated with enhanced mixing along sloping isentropes.

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1. Introduction

[2] Transpacific transport has been observed to bring east Asian gaseous and particulate pollutants to North America [e.g., *Jaffe et al.*, 1999, 2001, 2003; *Jaeglé et al.*, 2003; *Berntsen et al.*, 1999; *Kotchenruther et al.*, 2001; *Heald et al.*, 2003; *Price et al.*, 2003; *Hudman et al.*, 2004]. Asian pollutants are expected to have an increasing impact on North American air quality as east Asia continues rapid industrialization [*Jacob et al.*, 1999]. This has motivated numerous studies of transpacific pollutant transport including aircraft campaigns (for an overview, see *Jacob et al.* [2003] and *Parrish et al.* [2004]) and detailed studies of associated events [e.g., *Cooper et al.*, 2004], as well as model-based investigations of the climatological properties of transpacific transport [e.g., *Stohl*, 2001; *Stohl et al.*, 2002; *Holzer et al.*, 2003, 2005; *Liu et al.*, 2005; *Liang et al.*, 2004, 2005]. Of particular note for our work here is the study by *Liang et al.* [2004], where simulations of carbon monoxide (CO) from the GEOS-CHEM model [*Bey et al.*, 2001] are used to analyze a 15-month record of CO measurements from Cheeka Peak observatory (CPO, located at 48.3°N, 124.6°W) in terms of transport events and import/export mechanisms. Interestingly, *Liang et al.* [2004] suggest that boundary layer transport across the entire Pacific is responsible for 75% of the transport events reaching the lower troposphere in the vicinity of CPO. The degree to which east Asian air follows low-level paths to North America is an interesting, basic question about tropospheric transport in its own right. In addition, low, mid, and upper level paths potentially deliver different trace species to North America, because they are exposed to different deposition and chemical processes.

[3] In this paper we systematically quantify the role of low-level transport in bringing east Asian air to the North American west coast surface. As in the work by *Holzer et al.* [2003, 2005], we employ transit-time distributions. To calculate the effect of low-level paths, we define an additional distribution, which is the mass fraction of east Asian air that never exceeded a specified threshold height. If that threshold height is the model's prognostic planetary boundary layer height, we find that essentially none of the east Asian air is able to make it across the Pacific. Low-level paths confined below ~2.2 km, however do make a significant contribution to the summer and springtime surface climatology over the North American west coast. The fractional contribution of the low-level paths to summertime transport events at the North American west coast surface is comparable to their contribution to the climato-

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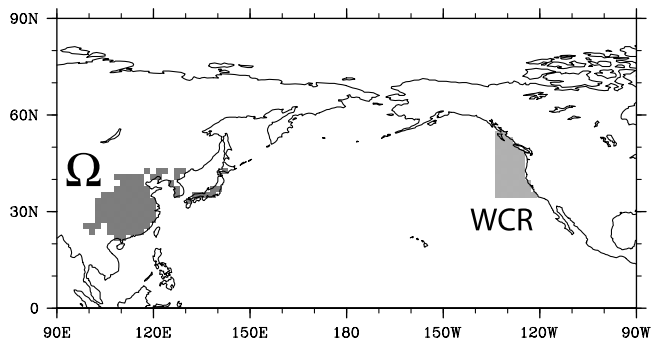


Figure 1. East Asian contact region, Ω, used to calculate the air mass fractions $\mathcal{G}(\mathbf{r}, t|\Omega, t')\,dt'$ and $\mathcal{G}_h\,(\mathbf{r}, t|\Omega, t')\,dt'$ at $(\mathbf{r}, t)$ that had last contact with Ω during the interval $(t', t' + dt')$. The Ω region has an area of 3.7×10^6 km^2 and a mean elevation of 700 m. To quantify the influence of low-level transpacific transport on the surface composition of the North American west coast, we focus on the West Coast Receptor (WCR) region.

logical surface means. The contribution of the low-level paths to the column burden is negligible.

2. Diagnostics of East Asian Air Mass Fraction

[4] As in the work by *Holzer et al.* [2003, 2005], we base our analysis on the transit-time pdf, $\mathcal{G}$, which is defined so that $\mathcal{G}(\mathbf{r}, t|\Omega, t')dt'$ is the mass fraction of an air parcel at point $\mathbf{r}$ and time t that had last contact with the surface patch, Ω, during the time interval $(t', t' + dt')$. To determine the transport by low-level paths, we also calculate the conditional transit-time pdf, $\mathcal{G}_h(\mathbf{r}, t|\Omega, t')$, defined so that $\mathcal{G}_h(\mathbf{r}, t|\Omega, t')dt'$ is the mass fraction of fluid elements at $(\mathbf{r}, t)$ that had last Ω contact during $(t', t' + dt')$, but that have never exceeded a specified height threshold, h. The threshold h is a function of horizontal location, and generally also time. Thus $\mathcal{G}_h$ represents the part of $\mathcal{G}$ due to fluid elements whose paths lie entirely below h. We concentrate on the east Asian "pollution" region Ω as defined by *Holzer et al.* [2003] (see Figure 1). We will refer to $\mathcal{G}_h(\mathbf{r}, t|\Omega, t')$ as "Ω_h air," and to $\mathcal{G}(\mathbf{r}, t|\Omega, t')$ as "Ω air," of age or transit time $\xi = t - t'$.

[5] To compute $\mathcal{G}$ and $\mathcal{G}_h$, we use MATCH (Model of Atmospheric Transport and Chemistry), a three-dimensional global model of the atmosphere developed by *Rasch et al.* [1997] that uses the mass-conserving SPITFIRE (Split Implementation of Transport using Flux Integral Representation) flux algorithm [*Rasch and Lawrence*, 1998]. We drive MATCH with T62 NCEP reanalysis data [*Kalnay et al.*, 1996; *Kistler et al.*, 2001] on a Gaussian grid of 94 latitudes and 192 longitudes (~1.9° × 1.9°), with 28 hybrid levels up to ~3 mbar. A natural choice for the threshold height, h, is the local planetary boundary layer height, h_{pbl}, which is computed prognostically in MATCH. However, we found that virtually no air was transported entirely within the shallow marine boundary layer right across the Pacific. Because of the suggestion of transpacific transport at boundary layer levels by *Liang et al.* [2004], we chose $h = \max(h_0, 1.1 \times h_{\mathrm{pbl}})$, with $h_0 = 2.2$ km, which corresponds to ~770 mbar. We discuss the sensitivity of our results to this choice for h_0 in the final section.

[6] The distributions $\mathcal{G}$ and $\mathcal{G}_h$ are calculated as the response to a pulse in surface mixing ratio on Ω. For both $\mathcal{G}$ and $\mathcal{G}_h$ mixing ratio is specified for the lowest model level over Ω as a day-long, 00Z to 00Z, square pulse of amplitude 1/day. Elsewhere on the Earth's surface, we enforce zero-flux boundary conditions, as in the work by *Holzer et al.* [2003, 2005]. For $\mathcal{G}_h$, we additionally apply a zero-mixing-ratio boundary condition at the threshold height h, by zeroing $\mathcal{G}_h$ at grid points above h at every time step. The response at time t (the "field time") to a mixing ratio pulse that occurred during day t' (the "source time") gives the mass fraction of air at time t that had its last contact with Ω during the 24-hour period of day t', which in the case of $\mathcal{G}_h$ is conditional on that air never having ventured above the threshold height. To determine climatological averages denoted by angle brackets $\langle \ldots \rangle$, we compute $\mathcal{G}(\mathbf{r}, t|\Omega, t')$ and $\mathcal{G}_h\,(\mathbf{r}, t|\Omega, t')$ for 3 years of source days t' from 1 September 1998 to 31 August 2001, the same period used for the study by *Holzer et al.* [2005]. Our analyses are thus based on a substantial data set of 2190 time-evolving tracers. Daily averages of both $\mathcal{G}$ and $\mathcal{G}_h$ and the corresponding meteorological fields are archived for transit times $\xi \equiv t - t'$ up to 30 days.

[7] The climatological means of the transit-time pdfs, or their vertical integrals, are defined as the average over an ensemble of realizations at fixed transit time $t - t'$ [*Holzer et al.*, 2003]. We consider seasonal ensembles corresponding to source times t' in a given 3-month period for the 3 years available and adopt the conventional definitions for seasons: DJF, MAM, JJA, and SON. The climatology of transit-time partitioned transpacific transport was presented by *Holzer et al.* [2005] in terms of $\langle \mathcal{G} \rangle$ and the fluctuations of the column burden of $\mathcal{G}$ over western North America. Here we focus on the contribution of low-level paths to transpacific transport, particularly on their influence on surface mixing ratios. To eliminate the effects of mountainous terrain reaching into the midtroposphere, we have defined our west coast receptor (WCR) region only over the ocean as shown in Figure 1. Our findings are not sensitive to the choice of receptor region. For robust results, we opted for a finite area rather than analyzing mixing ratio only for the grid box containing CPO.

3. Impact of Low-Level Paths on the Seasonal Means

[8] Figure 2 shows the WCR-averaged seasonal means of the mass fraction of east Asian air in each 24-hour transit-time interval at the surface and vertically integrated (column burden) as a function of transit time. The local mass fraction in a 24-hour transit-time interval is calculated as $\Delta t\,\mathcal{G}$, and the column burden per unit area (column burden, for short) in a 24-hour transit-time interval is calculated as $\Delta t \int_0^{p_s} \mathcal{G} dp/g$, where $\Delta t = 24$ hours, p_s is surface pressure, $g = 9.81$ m s^{-2}, and $\mathcal{G}$ is computed as described in section 2. The low-level paths make a very small contribution to the WCR-averaged column burden with maximum contributions of 1.7, 2.9, 4.2, 1.2% for DJF, MAM, JJA, and SON, respectively. However, the low-level paths do have a significant influence on the mass fraction of east Asian air at the surface in summer and spring. At the mode of $\langle G_h \rangle$ (that is, at the transit time for which $\langle G_h \rangle$ is peaked), the low-level paths

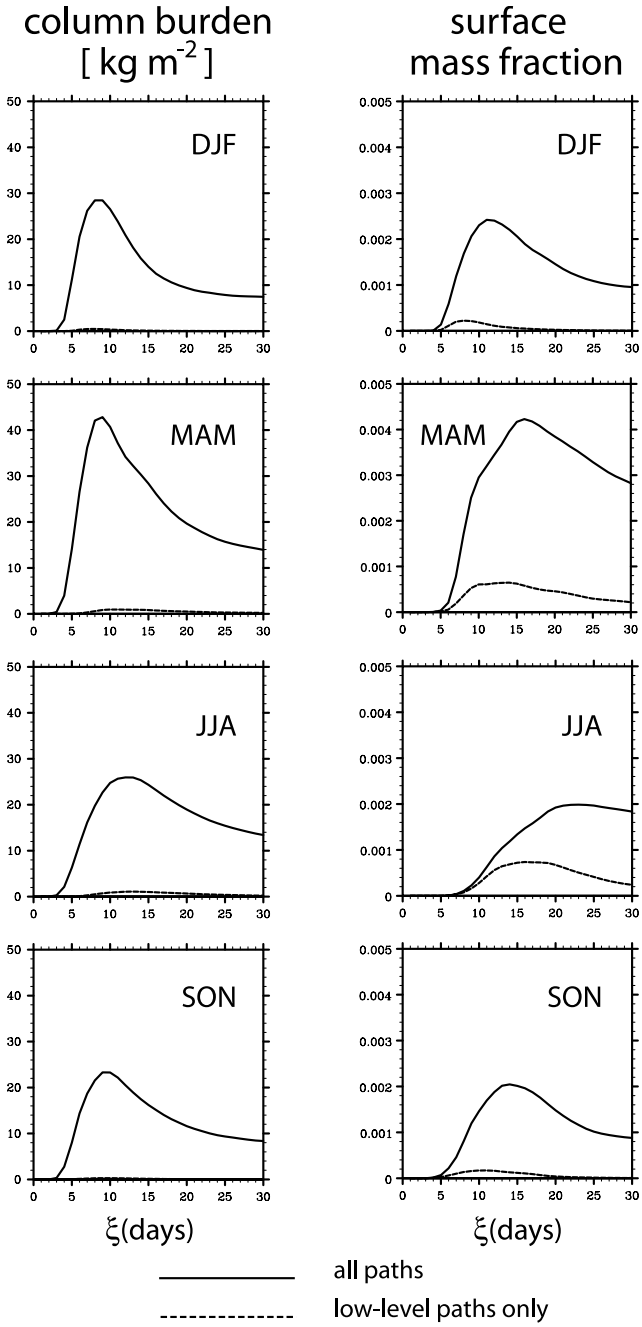


Figure 2. Seasonal mean, (left) WCR-averaged column burden and (right) surface mass fraction of east Asian air that had its last Ω contact during a 24-hour interval ξ days ago. The solid lines are for the full mass fraction of east Asian air due to all possible transport paths, while the dashed lines are for the mass fraction of east Asian air that never ventured above $h \sim 2.2$ km.

contribute a fraction $\langle G_h \rangle / \langle G \rangle$ of 13, 16, 50, 10% for DJF, MAM, JJA, and SON, respectively. The absolute magnitude of $\langle G_h \rangle$ at its mode is comparable for JJA and MAM. In the following we will focus primarily on JJA, because it is the season for which low-level paths make a large absolute and the largest relative contribution to the surface mixing ratio of Ω air.

[9] The surface mass fraction of Ω air is highly variable, and this variability is a function of transit time. Figure 3 shows the probability distributions of the WCR-averaged Ω and Ω_h air mass fractions in JJA at the surface for each 24-hour transit-time interval together with the climatological average and standard deviation. The fluctuations of both Ω and Ω_h air are seen to be highly skewed, with a most probable value that for JJA is near zero for the entire range of transit times. The peak variability occurs around $\xi = 13$ days for both Ω and Ω_h air. The seasonality and variability of the vertical structure of 13-day-old WCR-averaged Ω air are shown as a time series in Figure 4 (top). The corresponding time series for Ω_h air (Figure 4, bottom) shows that low-level paths make highly episodic contributions to the east Asian air mass fraction over the WCR region mostly during summer and late spring. The summertime episodes of low-level transport can contribute substantially to the lower column.

[10] The seasonal mean spatial distribution at the surface of 13-day-old Ω air is shown in Figure 5. The surface pools of Ω air in the region of the Pacific High visible for DJF, MAM, and SON, are absent for Ω_h air. This corroborates the finding by *Holzer et al.* [2005] that these pools are formed by subsidence from aloft and not by low-level transport. By contrast, although JJA has much less Ω air in the region of the Pacific High, the small amount present is to a significant degree also seen in the Ω_h air, confirming the importance of exclusively low-level transport for JJA. Low-level transpacific transport contributes most to the 13-day-old surface mixing ratio NE of the source region over the sea of Okhotsk during MAM and JJA. Note that while during JJA low-level paths contribute substantially to the mixing ratio over the NE Pacific, inland from the North American coast large surface mixing ratios result from elevated terrain accessing Ω air transported aloft.

[11] To further contrast summertime transport with that of the other seasons, and to reveal the main climatological transport mechanisms and pathways that operate during different seasons, it is useful to consider the zonal average of the Ω- and Ω_h-air mass fraction as a function of transit time, as shown in Figure 6, superposed on the zonal average of the (dry) potential temperature. To isolate transpacific transport, we restrict the zonal average to longitudes 141°E to 126°W.

[12] For JJA, Ω air is primarily injected convectively into the upper troposphere, but there is also distinct low-level outflow. The summertime Pacific troposphere is very stable with weak baroclinicity, so that nearly half of the 13-day-old east Asian air near the Pacific surface has never ventured above ~2.2 km (see also Figures 2 and 5). The upper air mass experiences relatively little vertical transport with a core descent rate consistent with diabatic cooling.

[13] During DJF, east Asian outflow occurs primarily at low levels followed by isentropic transport aloft and northward, consistent with "warm conveyor belts" [e.g., *Stohl*, 2001; *Stohl et al.*, 2002; *Liu et al.*, 2003]. Low levels are well connected to the free troposphere by sloping isentropic surfaces. As a result the low-level air rapidly makes contact with the boundary condition at ~2.2 km and disappears from the zonal average of Ω_h air (low-level paths only). During DJF, east Asian air arrives at the eastern Pacific surface by being mixed down isentropically from the free troposphere. In addition, air on the southern flank of the Ω-air plume experiences subsidence over the region of the Pacific High.

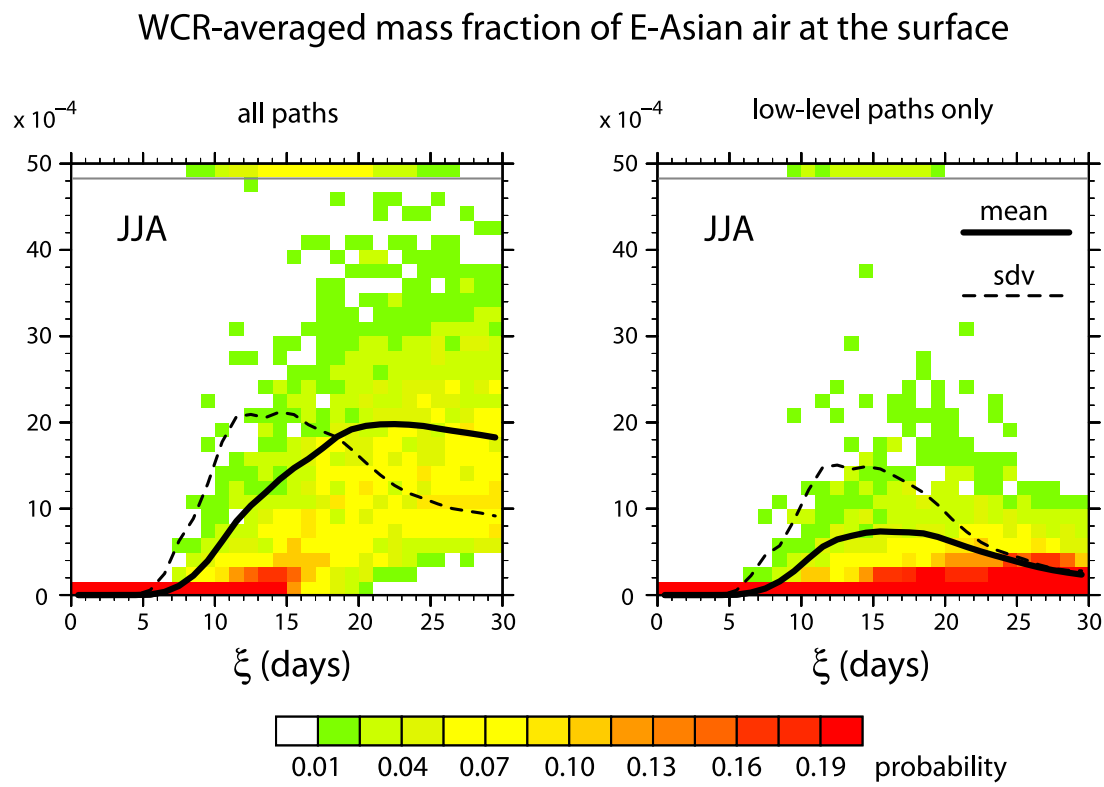


Figure 3. JJA seasonal mean, WCR-averaged mass fraction of east Asian air at the surface that had its last Ω contact during a 24-hour interval ξ days ago (solid line) and corresponding standard deviation (dashed line). Color shading indicates normalized histograms of the surface mass fraction of east Asian air in each 24-hour transit-time interval, expressed as the probability of finding the column burden in a given bin (which are the size of the color pixels). The probability in bins positioned above an air mass fraction of 0.003 has been accumulated in the topmost bin shown.

[14] During MAM, Ω air enters the Pacific troposphere at all levels. While a small fraction of the low-level air survives for 13 days and makes it across the Pacific, there is strong isentropic transport at midlatitudes, that, as for DJF, lofts low-level Ω air over the western Pacific and mixes Ω air from the midtroposphere to the NE Pacific surface. The evolution of the zonal averages suggest a separate pathway in the more stable and less baroclinic subtropical flank of the plume.

[15] During SON, there is evidence of convective injection into the upper troposphere with separate low-level outflow, similar to JJA. However the troposphere is much less stable in SON, and the low-level outflow is isentropically well connected to the free troposphere. Consequently, the low-level east Asian air does not survive for long before venturing above ~2.2 km. During SON, east Asian air is organized into particularly distinct subtropical and midlatitude plumes. The midlatitudes are characterized by Ω air spreading along sloping isentropes as for DJF and MAM, while a separate Ω-air plume is formed in the more stable subtropics, where isentropes are more horizontal and diabatic subsidence is likely to play a more important role.

4. Surface-Event Weighted Composites

4.1. Definition of Weighted Composites

[16] To reveal the typical evolution of Ω air during transport events for which the receptor-averaged column burden exceeds one standard deviation, *Holzer et al.* [2005] calculated lagged, weighted composites based on the column burden over western North America. These composites revealed that transport events associated with enhanced column burdens are primarily associated with transport through the mid and upper troposphere during all seasons.

[17] Here we focus on the typical evolution of events that lead to enhanced surface mixing ratios of Ω air over the WCR region. We therefore calculate lagged, weighted composites based on the WCR-averaged surface mixing ratio of ξ-day-old Ω air exceeding one standard deviation (our definition of "event" for ξ-day-old air). More precisely, surface-event composites, $\langle X\rangle_\psi$ (**r**; ξ, τ), at a lag τ, of field X(**r**, t) are calculated as

$$\langle X\rangle_\psi(\mathbf{r};\xi,\tau) = \langle X(\mathbf{r},t-\tau)\psi(t;\xi)\rangle / \langle\psi(t;\xi)\rangle \quad , \qquad (1)$$

where ψ is the standardized, that is, the quadratically detrended, zero-mean, unit-variance time series of the WCR-averaged surface mass fraction of ξ-day-old Ω air (due to all paths) that has been zeroed when $\psi < 1$, to exclude days for which the WCR surface mixing ratio falls below one standard deviation. The angle brackets in (1) denote averages over days t within the season of interest, for all 3 years studied. These are also the times for which the corresponding standardization of ψ is performed.

[18] The overall picture of the relative contributions of the low-level paths to the event composites is qualitatively

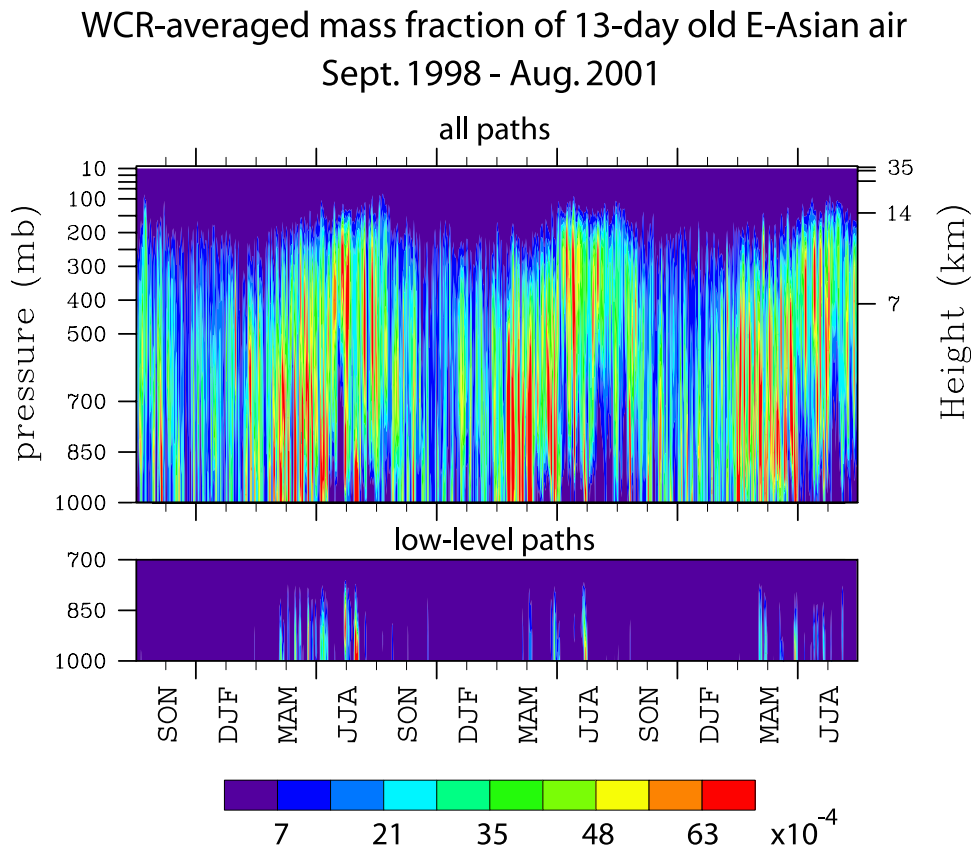


Figure 4. Vertical distribution (linear in pressure) of the daily WCR-averaged mass fraction of air that had its last contact with Ω during the 24-hour period 13 days ago, as a function of time for the full 3-year study period from 1 September 1998 to 31 August 2001. (top) Mass fraction of east Asian air transported by all possible paths throughout the troposphere and (bottom) mass fraction of east Asian air that never ventured above $h \sim 2.2$ km.

similar to that for the climatological means. For JJA, low-level paths dominate the event-composited, WCR-averaged Ω-air mass fraction at the surface, while for the other seasons the contribution of the low-level paths is much smaller. For the transit times, ξ, with the largest composites of the WCR-averaged surface mass fraction at lag $\tau = 0$, the low-level contributions are 17, 23, 69, and 13% for DJF, MAM, JJA, and SON, respectively. These maximum composites occur at approximately the transit time, ξ_{max}, for which $\mathcal{G}$ has maximum variance: ~13 days for JJA (see Figure 3) and ~7 days for the other seasons. For $\xi > \xi_{max}$, the relative contribution of low-level paths declines gradually with ξ for all seasons, as more time becomes available to mix east Asian air to the surface. For $\xi < \xi_{max}$, the magnitude of the composites falls rapidly to zero. At the shortest transit times of 3 or 4 days, a few rare events have low-level contributions of more than ~50% to small composites, which is most pronounced for SON and MAM. However, the concentration of any actual tracer is an aggregate over transit times [e.g., *Holzer et al.*, 2003, 2005], so that for any species with a lifetime of ~7 days or more, extremes in the WCR-averaged tracer concentration will be dominated by the large events for which the low-level contribution is minor in all seasons except JJA.

[19] Because low-level paths contribute substantially to event composites only for JJA, for which the large events occur for $\xi \sim 13$ days, we focus here on surface event composites based on ξ = 13-day-old air. The qualitative character of the composites is not sensitive to the choice of ξ, but the number of days contributing to the JJA events declines as ξ is reduced, making the composites less robust. For ξ = 13 days, and our threshold of one standard deviation, the three JJA periods of our data set contribute 23 days to the surface event composites, which are clustered into 7 separate events. It is worth pointing out that event composites are very insensitive to the choice of threshold. The reason for this is that the fluctuations of ξ-day-old Ω air at the surface are highly non-Gaussian, corresponding to a time series of very small values punctuated by large spikes (see Figures 3 and 4).

4.2. Composited NH Meridional Average

[20] Figure 7 shows the JJA evolution of the surface-event composited Northern Hemisphere meridional average with decreasing lag time, τ, before WCR landfall at age 13 days. We can think of these composites as showing the average evolution of Ω and Ω_h air that results in enhanced (more than one standard deviation) surface mixing ratios of 13-day-old Ω air (all paths) on the WCR region. Distinct summertime upper and lower tropospheric paths are evident in the composites, as they are in the zonally averaged climatologies (Figure 6). The composites of Ω_h air (based

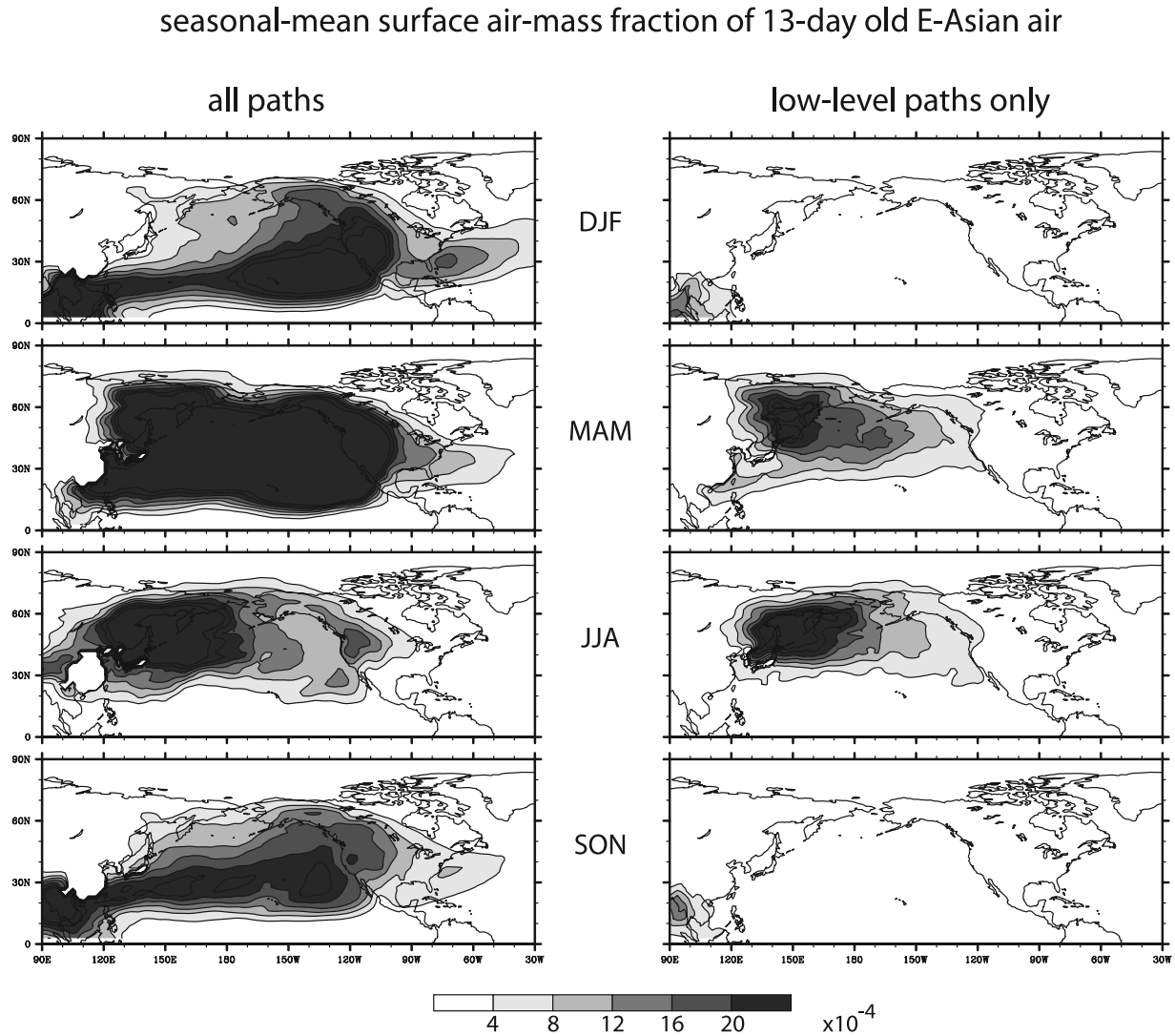


Figure 5. Climatological east Asian air mass fraction at the surface that had its last Ω contact during the 24-hour period 13 days ago, for each season. (left) Surface air mass fraction due to all possible paths and (right) surface air mass fraction due to paths that never ventured above $h \sim 2.2$ km.

on surface events of Ω air due to all paths), however, show that only ~50% of the 13-day-old Ω air at the North American west coast surface is transported across the Pacific entirely at low levels (Figure 6 plots for $\tau = 0$). The remainder must come from the downward mixing of Ω air injected into mid and upper levels over the source, and from Ω air that started at low levels, was lifted above ~2.2 km, and then descends again toward the surface. These vertical transport processes are sufficiently weak so that the troposphere can retain distinct upper and lower level maxima in the east Asian air mass fraction. Surface-event composites of the NH meridional average for the other seasons (not shown), show a single maximal region of east Asian air that descends to the surface upon landfall.

[21] The geographical distribution for JJA of the surface-event composited Ω-air mass fraction at the surface is shown in Figure 8. This shows the average evolution of Ω and Ω_h air at the surface with decreasing lag τ, that will lead to WCR surface events of 13-day-old Ω air. In the early stages (4 and 7 days since last Ω contact, or lags $\tau = 9$ and 6 days, respectively), the surface signatures of Ω and Ω_h air are almost identical. Thus, in the early stages of summertime transpacific transport events, east Asian air transported at low levels has not ventured above ~2.2 km, and that injected into the upper troposphere has had no chance to mix down below ~2.2 km. By a lag of $\tau = 3$ days, differences in Ω and Ω_h air at the surface are visible. Upon land fall at $\tau = 0$, the Ω_h air mass fraction accounts for roughly 80% of the peak surface mixing ratio of 13-day-old Ω air during events.

4.3. Composited Pacific Zonal Averages and Other Seasons

[22] To contrast transport leading to surface events during JJA with that during the other seasons, and to identify the dominant transport mechanisms leading to surface events, we show in Figure 9 surface-event composited 141°E–126°W zonal averages of the Ω and Ω_h air mass fraction with superposed contours of the (dry) potential temperature for all seasons. The composites are again based on surface

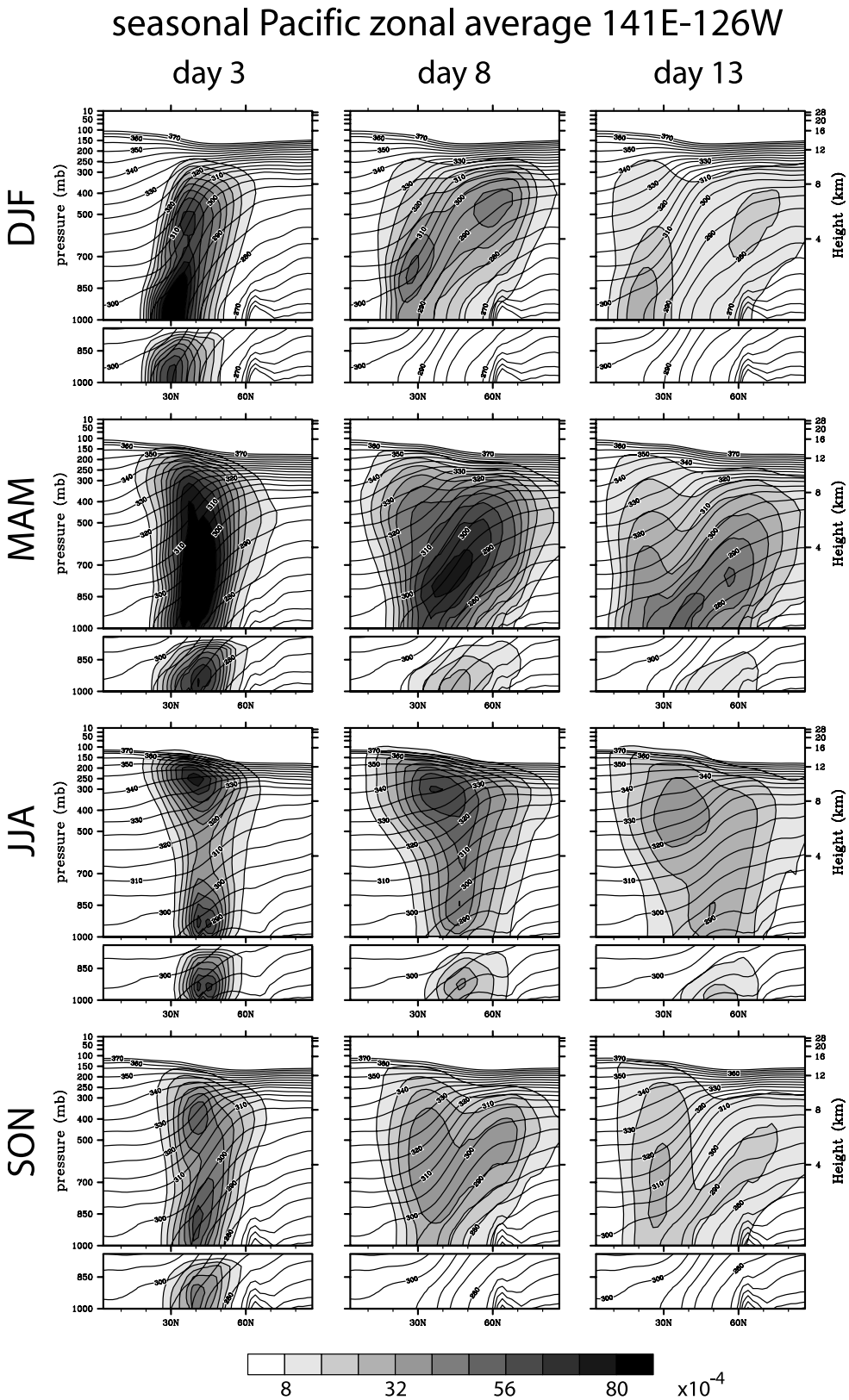


Figure 6. Zonal averages from 140.6°E to 125.6°W of the climatological east Asian air mass fraction that had its last Ω contact during the 24-hour period indicated, for each season. The labeled contours indicate the potential temperature with a 5-K contour interval. The panels with all vertical levels show the east Asian air mass fraction due to all possible paths, while the narrow panels show the east Asian air mass fraction due to only low-level paths.

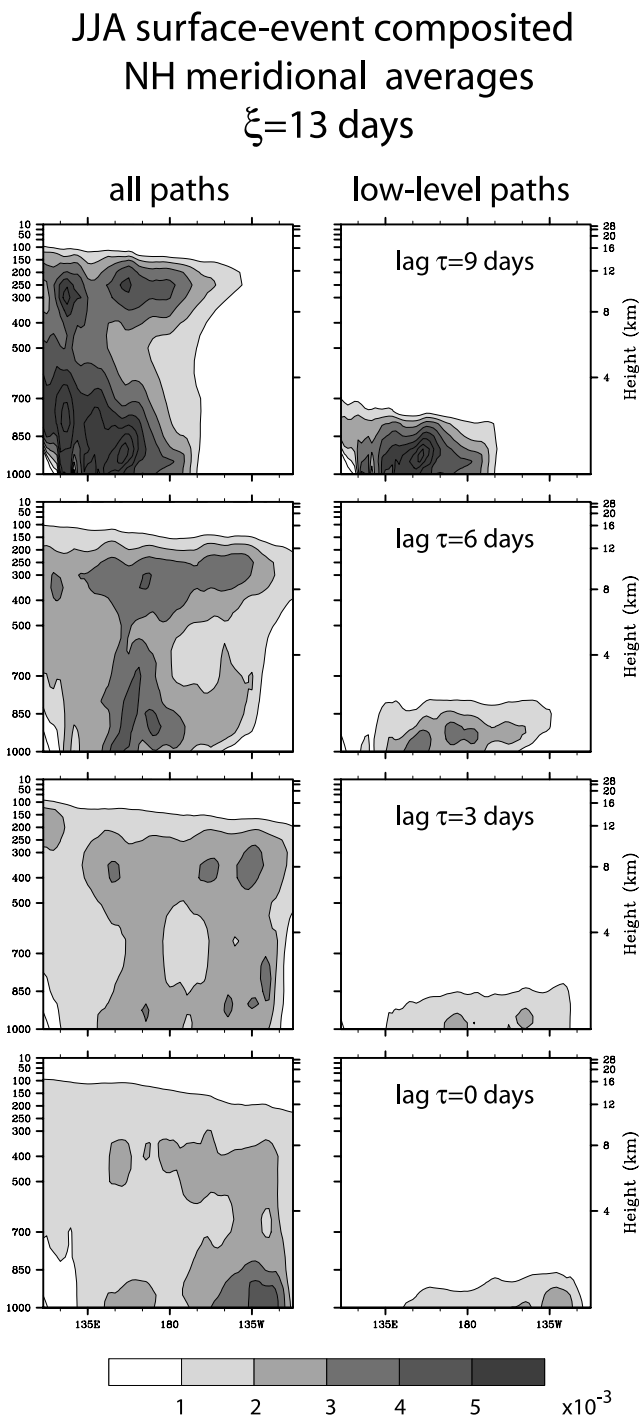


Figure 7. Surface-event composites (see text for definition) for JJA of the NH meridional average of the east Asian air mass fraction conditioned on the standardized time series of ξ = 13-day-old, WCR-averaged surface mass fraction of Ω air falling above one standard deviation, and lagged by τ days, as indicated. Shown are longitudes 110°E to 110°W, spanning the North Pacific. (left) Composites of the full (all paths) east Asian air mass fraction and (right) composites of the east Asian air mass fraction due to low-level transport only. Composites of both are based on WCR surface events of the full surface mixing ratio.

events for which WCR-averaged 13-day-old Ω air due to all possible paths exceeds one standard deviation, and they are shown at a lag of τ = 3 days (that is, 10-day-old air has been composited, 3 days before the WCR surface event). For the 3-year study period, there are 43, 37, 23, 37 event days clustered into 22, 17, 7, 19 separate events for DJF, MAM, JJA, and SON, respectively. Surface event composites based on 7-day-old air, which at a lag of one day are at a similar stage in their evolution, are qualitatively similar.

[23] For all seasons the transport pathway most important in bringing east Asian air to the WCR surface is enhanced in composites relative to climatology (Figure 6). During JJA the composited Ω air still shows distinct upper and lower tropospheric plumes, but the lower plume dominates the composite, while climatologically the upper plume carries the bulk of the east Asian air. For DJF, MAM, and SON the isentropic midlatitude plume dominates, with the subtropical plume being relatively suppressed. This suggests that during all seasons except summer, isentropic descent is the most important mechanism for bringing east Asian air to the WCR surface.

[24] By definition, Ω_h air follows paths that never pass above ~2.2 km, and therefore cannot access the isentropic midlatitude transport mode. Consequently the Pacific zonal averages of the surface composites of 10-day-old Ω_h air are negligible for DJF and SON and not visible on the scale of Figure 9. For MAM, some Ω_h air is visible, but it is only a small fraction of the full Ω-air surface-event composite. For JJA, Ω_h air represents roughly 75% of the full Ω-air surface composite (see also Figure 8 for τ = 3 days), emphasizing the importance of low-level paths for summertime surface events.

5. Summary and Conclusions

[25] The point of this work has been to quantify the contribution of low-level paths to transpacific transport, with emphasis on transport to the surface of the North American west coast. To that end, we have used MATCH driven by NCEP reanalysis data to compute daily averages for a 3-year period of the mass fraction of east Asian air partitioned according to the transit time since last contact with its source region, Ω (Figure 1). We computed the mass fraction due to all possible paths (Ω air, transit-time distribution $\mathcal{G}$) and, separately, due to only paths that lie entirely below $h \sim 2.2$ km (Ω_h air, conditional distribution $\mathcal{G}_h$). Both climatological averages and composites based on surface events over the WCR region (Figure 1) have been analyzed.

[26] For JJA, low-level paths account for ~50% of the climatological surface mixing ratio of east Asian air over the WCR region. The absolute contribution of low-level paths is similar during MAM, but, because MAM transport to the surface is much stronger, the exclusively low-level transport contributes only ~16% of the total at the mode of $\mathcal{G}$. For DJF and SON, low-level transport contributes even less.

[27] In as far as MATCH produces a realistic boundary layer height, we find negligible transpacific transport entirely within the marine boundary layer. The low-level transport we document here takes place predominantly in the summertime, stably stratified lower marine troposphere. For all seasons, the contribution of low-level paths entirely

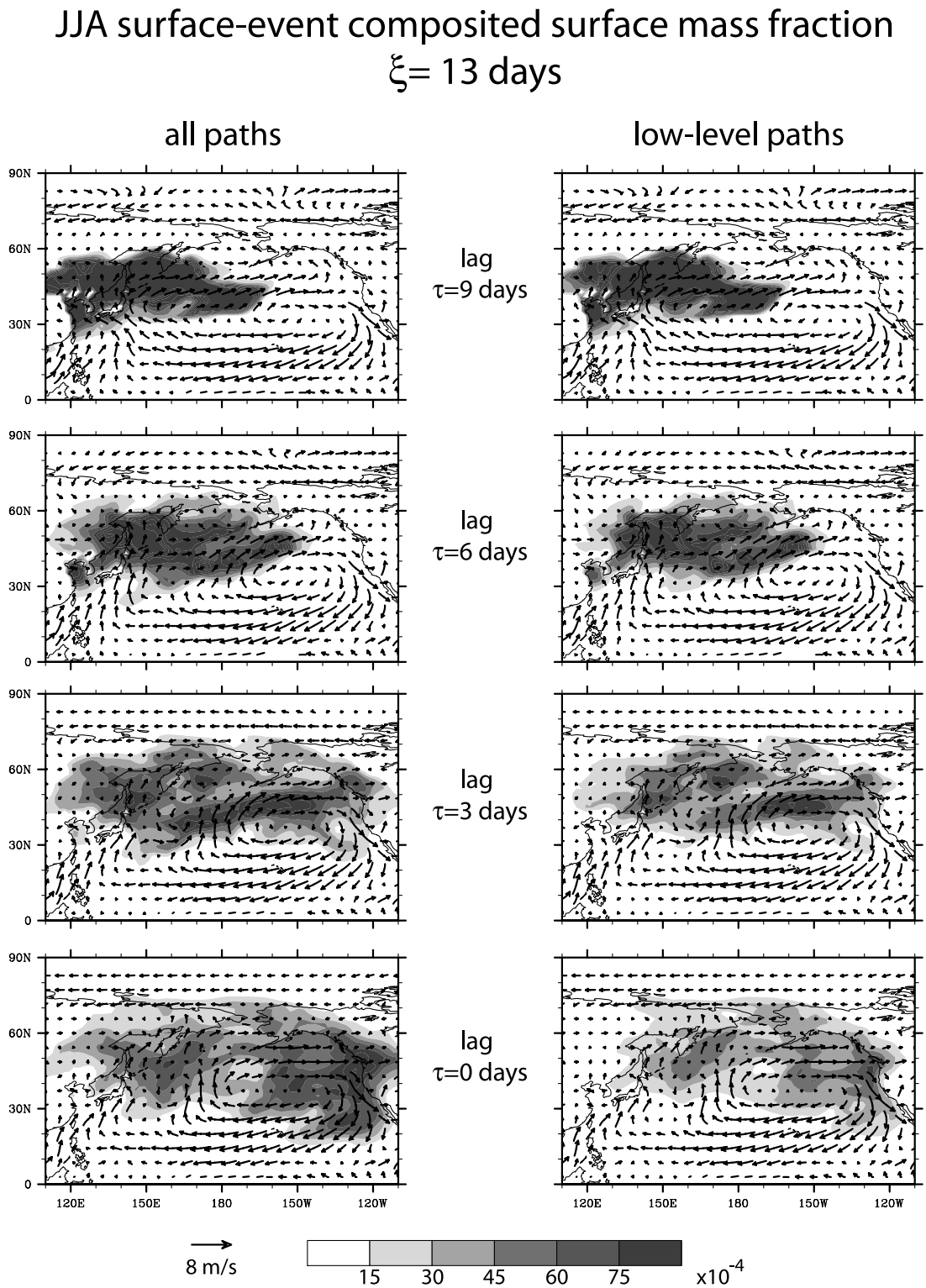
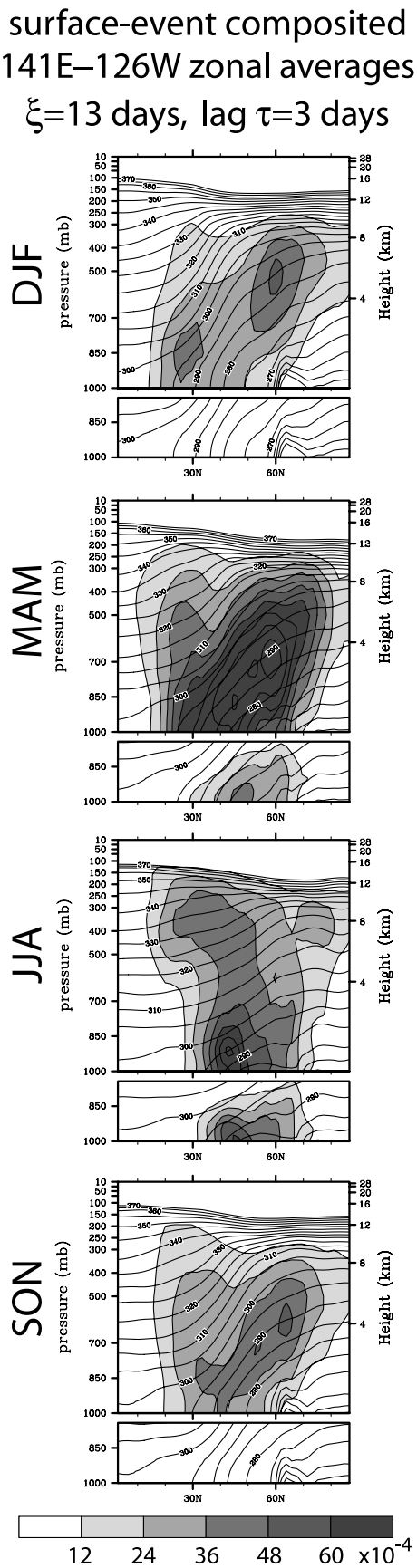


Figure 8. Surface-event composites for JJA of the lowest-model-level winds and east Asian air mass fraction conditioned on the standardized time series of ξ = 13-day-old, WCR-averaged surface mass fraction of Ω air falling above one standard deviation, and lagged by τ days, as indicated.

below ~2.2 km to the WCR-averaged column burden of east Asian air is negligible. The column burden is dominated by transport at mid and upper levels.

[28] Zonal averages of the transit-time partitioned, seasonal mean east Asian air over the Pacific show that JJA transpacific transport produces two distinct plumes: An upper tropospheric plume fed by convection over east Asia carrying the bulk of east Asian air, and a lower tropospheric plume fed by low-level outflow. Weak storm activity and stability of the summertime Pacific air column allow these



plumes to retain their identity as they travel across the Pacific. During the other seasons, a midlatitude plume that is mixed along sloping isentropes can be distinguished from a subtropical plume. The midlatitude plume consists of low-level outflow that is isentropically lofted over the western Pacific and then mixed down to the surface over the eastern Pacific. The subtropical plume appears to be fed convectively and traverses the Pacific at more stable subtropical latitudes. As a note of caution, we remind the reader that, while MATCH is driven by reanalysis data, convection and boundary layer mixing are parameterized and hence subject to model biases.

[29] The height threshold parameter of h_0 = 2.2 km for the definition of low-level paths was motivated by the suggestion of *Liang et al.* [2004] that transpacific transport within the boundary layer is significant for events of enhanced CO within 2 km of the surface at CPO. A systematic exploration of transport below the threshold height as a function of h_0 is computationally prohibitive because of the large number of tracers needed to calculate $\mathcal{G}_h$. However, the sensitivity to h_0 can roughly be estimated from the vertical structure of the climatological Ω-air plume. For JJA, we expect the least sensitivity because there are well separated lower and upper plumes. For the other seasons, the midlatitude plume is mixed along sloping isentropes so that raising h_0 should capture substantially more east Asian air, particularly for DJF and SON when the center of the midlatitude plume lies in the midtroposphere. Calculations with h_0 = 3.5 km for the single year September 1998 to August 1999 broadly confirm these expectations with increases of the WCR-averaged $\mathcal{G}_h$ at its mode by factors of 2.4, 2.2, 1.5, and 2.7 for DJF, MAM, JJA, and SON, respectively.

[30] Event composites were computed on the basis of 13-day-old Ω air at the WCR surface, ~13 days being the transit time for which this air has its maximum variability. These surface-event composites reveal the transport pathways most effective in bringing large amounts of east Asian air to the WCR surface. During JJA surface events, the low-level plume is enhanced compared to climatology, while for the other seasons surface events are associated with an enhanced midlatitude isentropic plume. During DJF, MAM, and SON, restricting transport to paths entirely below ~2.2 km excludes significant isentropic transport and mixing, resulting in small low-level contributions.

[31] Using the framework of conditional transit-time distributions, we have quantified the role of exclusively

Figure 9. Surface-event composites of the mass fraction of east Asian air (shaded contours) and of potential temperature (labeled contours, 5-K interval) zonally averaged from 140.6°E to 125.6°W. The composites are conditioned on the standardized time series of ξ = 13-day-old, WCR-averaged surface mass fraction of Ω air falling above one standard deviation, and lagged by τ days, as indicated. The panels with all vertical levels show the east Asian air mass fraction due to all possible paths, while the narrow panels show the east Asian air mass fraction due to only low-level paths. Composites of both are based on WCR surface events of the full surface mixing ratio. Note that the contour interval here is 12×10^4 versus 8×10^4 in

low-level paths in bringing east Asian air to the surface of the North American west coast. Our calculations lend support to *Liang et al.*'s [2004] finding that low-level transport contributes to events reaching the NE Pacific below 2 km. However, contrary to *Liang et al.*'s [2004] broader claim that most such events are due to low-level transport, we find that low-level transport is only important during summer and late spring.

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