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A Lamina-based Approach for Interpreting Variability in Ozonesonde Vertical Profiles

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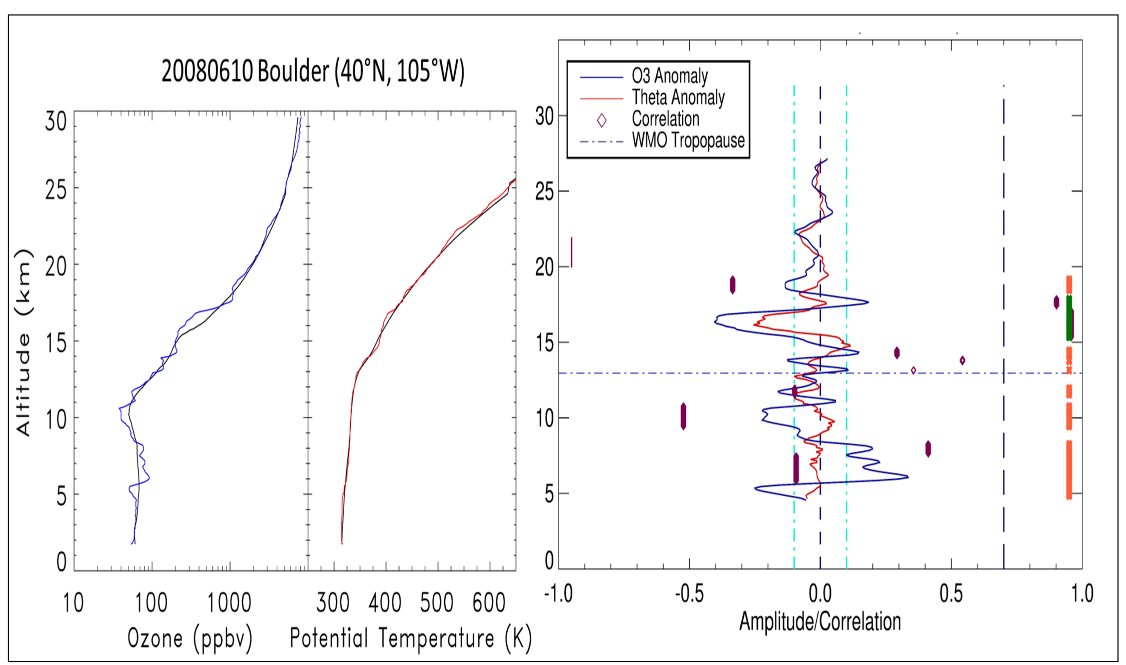
- We analyze a 25-year ozonesonde dataset and quantify ozone variability due to laminar features observed in balloon soundings of ozone and temperature (**boxes 1 & 2**).
- Ozone laminae, defined by perturbations > 10% from a basic state profile, and vertical scales between 0.2 and 2.5 km, account for more than one third of the overall variability seen in ozone (**box 3**).
- Coincident perturbations in ozone and potential temperature are used to identify features associated with gravity waves (GW), which make up 28% of all ozone laminae. The remaining 72% are classified as non-gravity wave (NGW) laminae (**box 4**).
- Sources and transport pathways for NGW ozone laminae are examined using back trajectories applied to individual laminae (**box 5**).

1 Data, Analysis Tools, and Methods

- NOAA/ESRL ozone dataset from Boulder, CO. 1991-2016, ~weekly frequency of balloon soundings, sampling during all seasons. L100 data at 100-m resolution.
- Profile-by-profile analysis using RIO SOL (Robust Identification of Observed Signatures in Ozone Laminae).
- Back trajectories from balloon soundings over 8-day period using trajectory code driven by winds and diabatic heating rates from MERRA-2.

2 Lamination in a Single Ozonesonde Profile

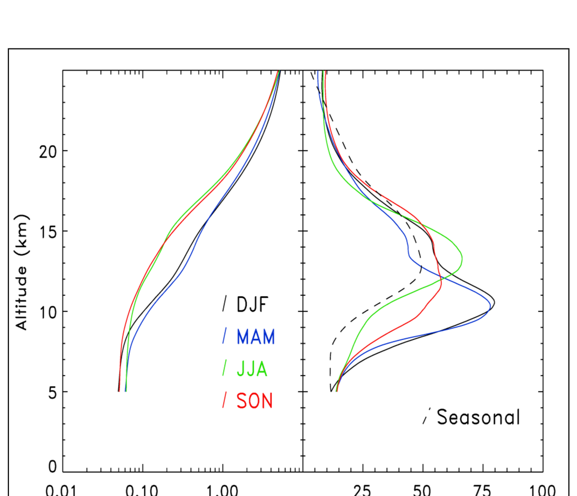


Vertical profiles of ozone (blue) and potential temperature (Θ, in red) from a Boulder sounding on 10 June, 2008. Also plotted are respective basic state profiles (black) derived using a low-pass filter designed to remove all variations on scales less than about 2.5 km (~1.5 km near the tropopause). The WMO (temperature gradient) tropopause is near 13 km altitude.

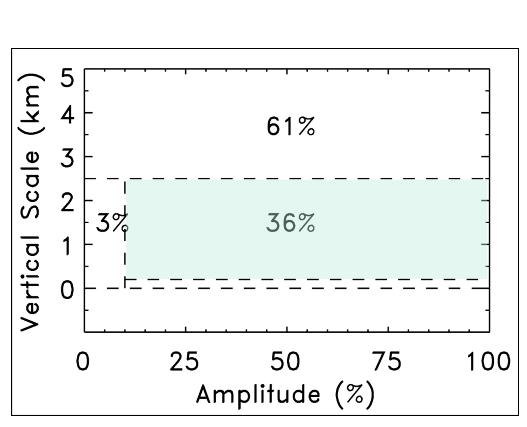
Deviations from the basic state larger than 10% are identified as laminae (e.g., Thompson et al., JGR, 2007). Two negative ozone laminae near 10 and 17 km are easily discernable by eye.

Anomalies in ozone (blue) and scaled anomalies in potential temperature (red) from differencing the sounding at left. Also plotted are the 10% minimum amplitude thresholds (cyan vertical dashed lines) used to identify laminae. Thick purple bars indicate the magnitude of the correlation coefficient between ozone and Θ anomalies. Where these are correlated, with r > 0.65, the ozone perturbation is labeled a **gravity-wave lamina (GW)** and marked with the green bar on the far right. For r < 0.65, it is labeled a **non-gravity wave lamina (NGW)** and marked by an orange bar on the right.

3 Laminae Contribution to the Overall Variance in Ozone

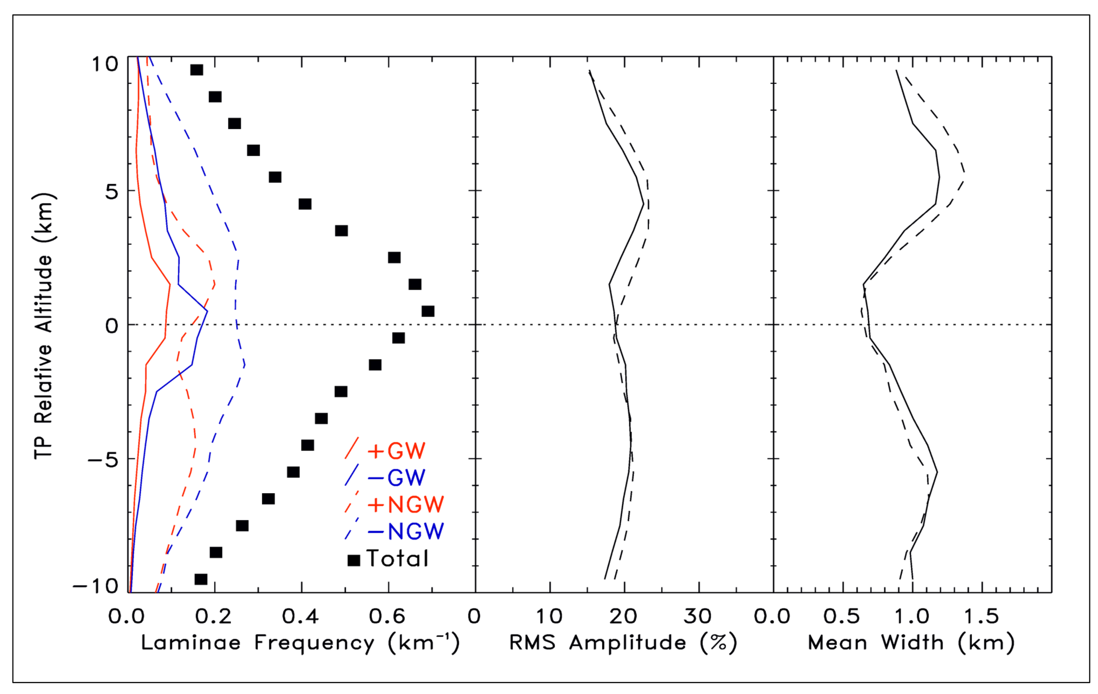


Left panel: 1991-2015 mean basic states of ozone for four seasons.
Right panel: intraseasonal standard deviation of basic states, along with comparable magnitude of seasonal variation (dashed).



Fraction of overall variance as a function of laminae amplitude and thickness. The top area at 61% is derived from basic state variance at left. Most of the remainder (36%) is due to the laminae identified here (highlighted area).

4 GW and NGW Laminae: Description & Climatologies

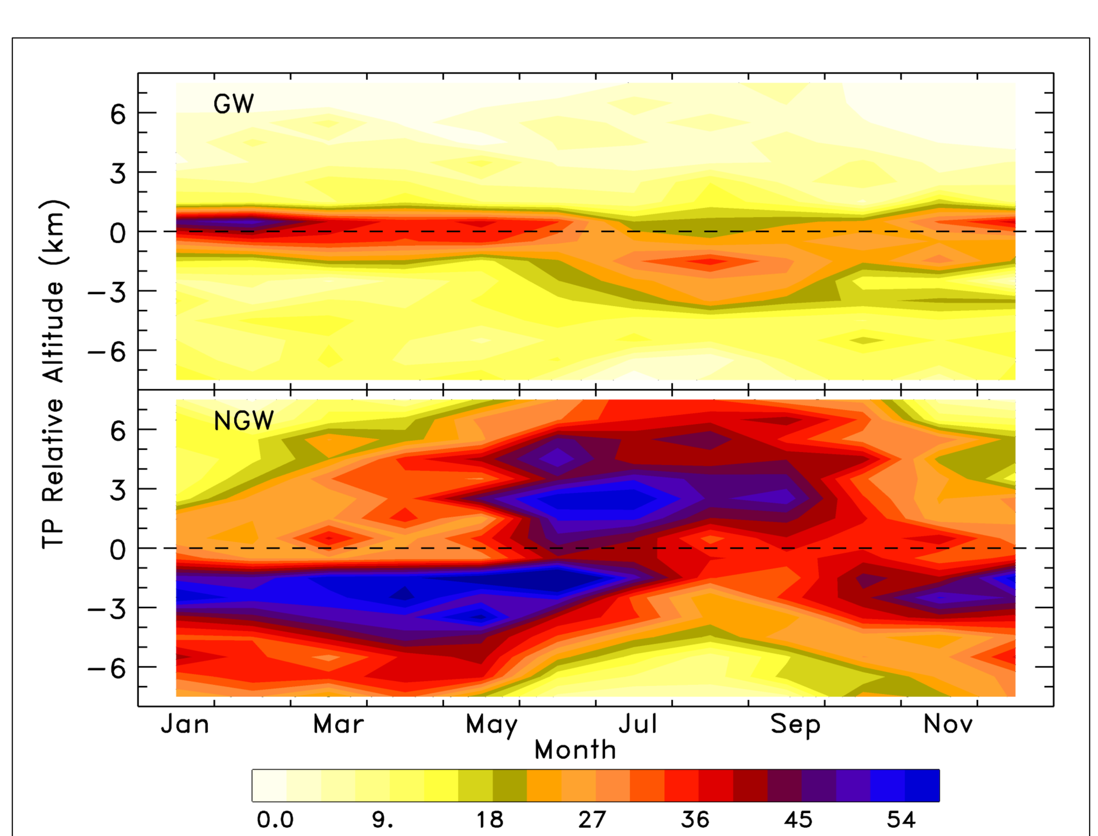


General characteristics of ozone laminae in altitude coordinates relative to the WMO tropopause.

Left panel: mean number of laminae detected per sounding within 1-km wide altitude bins. Black squares are frequencies for all laminae types and signs, solid lines show frequencies of GW laminae, dashed lines indicate NGW laminae, and red and blue colors indicate positive and negative anomalies, respectively.

Middle panel: profiles of RMS amplitudes for GW (solid) and NGW (dashed) ozone laminae. Amplitudes are based on the square of the mean relative anomaly within each lamina, and averaged over all laminae detected within corresponding relative altitude bins.

Right panel: profiles of mean laminae widths for GW (solid) and NGW (dashed) ozone laminae. Widths are defined as the full altitude range where the anomaly amplitude exceeds 10% along consecutive 100-m sampling intervals.

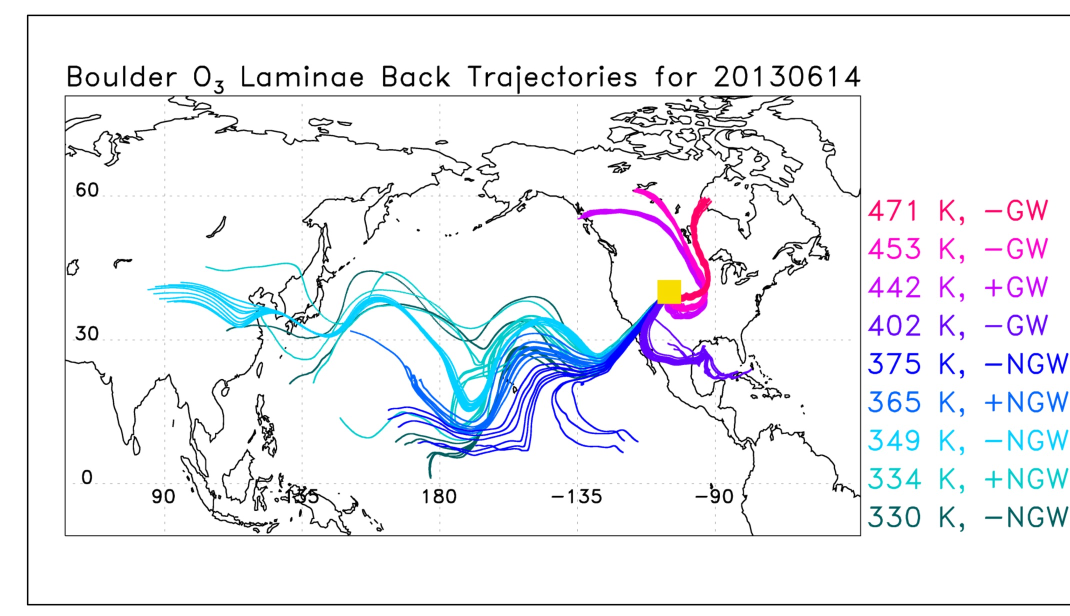


Climatology of ozone laminae frequency at Boulder as a function of month and altitude relative to the WMO tropopause for GW (top) and NGW (bottom) laminae.

GW laminae are detected most often near the tropopause during winter. Consistent with our results, climatologies of gravity wave momentum fluxes in the lower stratosphere indicate a wintertime maximum for this location (e.g. Geller et al., J. Clim., 2013).

NGW laminae are more prevalent in the upper troposphere during fall/winter/spring, shifting to the lower stratosphere during summer.

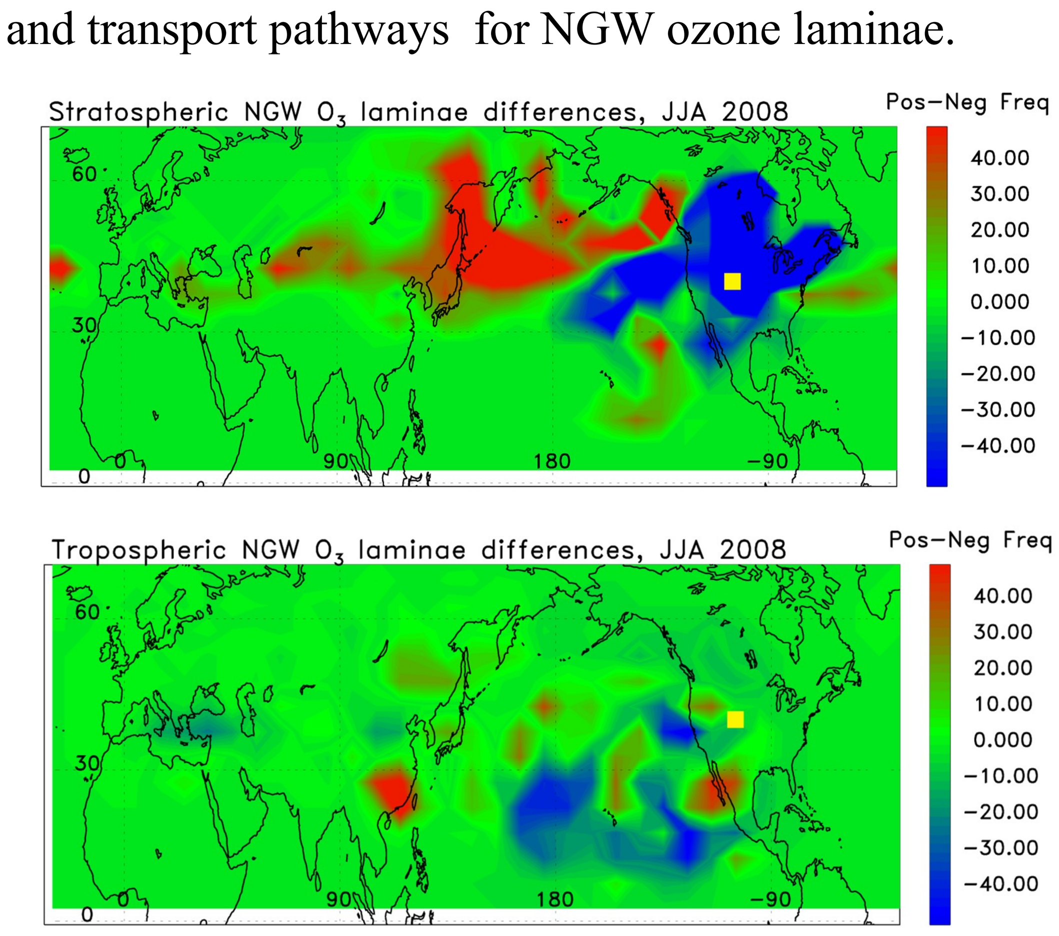
5 Back Trajectories for Ozone Laminae



8-day back trajectories for individual laminae detected in the Boulder ozone sounding on14 June 2013. Each color represents a cluster of 9 back trajectories around a 1°x1° lat/lon square centered on the sounding and at the θ level of each lamina. Central θ level and lamina type are indicated in the legend. The location of Boulder is shown by the gold square. The tropopause level is near 370 K for this sounding.

Note the large directional variability for stratospheric parcels, and the longer trajectory paths taken by parcels associated with upper tropospheric NGW laminae.

Lat/lon probability distribution functions (PDFs) for back-trajectory paths of ozone laminae were constructed to investigate the dominant source regions and transport pathways for NGW ozone laminae.



Differencing positive and negative amplitude PDF's largely removes clustering effects due to trajectory convergence over Boulder, and isolates source regions for individual lamina types

Top: Source regions for positive laminae (red) and negative laminae (blue) in the stratosphere. During this time, most negative stratospheric laminae originated over the northeast US and Canada, while positive laminae originated from the northern and western Pacific.

Bottom: Same as above, but for tropospheric NGW laminae. Most negative laminae originated from the tropical eastern and central Pacific, while positive laminae originated from SE Asia and Mexico.