Using GOES Layer Average Specific Humidity (GLASH) and Lagrangian Reverse Domain Filling Trajectories to Forecast Stratospheric/Tropospheric Exchange (STE)

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1. Objective

The goal of this research effort was to forecast the location of ozone enhancements in the troposphere that result from Stratospheric/Tropospheric Exchange (STE). Reverse domain filling (RDF) trajectories and Lagrangian Liapunov exponents were used to develop a mixing forecast for the upper-troposphere. Lagrangian simulations capture filamentary tracer structures associated with isentropic mixing, or stirring. Stirring is derived from shear in the large-scale flow and distorts the shape of air parcels through a process known as chaotic advection. Liapunov exponents provide a measure of this stretching rate, the deformation of the flow by velocity shear. The RDF technique has been successfully applied to diagnose mixing in the stratosphere (Pierce et al., 1993), and has been shown to simulate the physical cascade of tracer variability to smaller scales. The development of filaments in the upper troposphere should enhance the efficiency of small-scale mixing along the boundary between moist subtropical tropospheric air and dry, ozone-rich stratospheric air. Image loops of GOES Layer Average Specific Humidity (GLASH) a derived product (and a conservative quantity) appear to capture these filamentation and fragmentation processes that we associate with STE. In this sense, they have operational value, allowing us to diagnose STE in near real-time. We used both satellite imagery and sonde observations of upper tropospheric ozone to evaluate RDF forecasts made during the recent summer 2004 NASA INTEX mission. We also illustrate the value of post-mission RDF analyses to diagnose mixing in an event of STE observed during the 2000 Tropospheric Ozone Production about the Spring Equinox (TOPSE) field mission.

2. RDF Trajectories

Reverse-domain-filling is a trajectory mapping technique; parcel trajectories are initialized on a uniform grid at the intended time (a forecast or an analysis time). In the first case presented, we used a 48 hour forecast for the uniform grid, trajectories were computed backward in time, and constituent values (e.g. potential vorticity, or liapunov exponents) were mapped from the parcel positions at earlier times forward to the uniform grid at the forecast time.

RDF trajectories were initialized based on forecasts from the 40km Eta model, the operational mesoscale model run by the National Center for Environmental Prediction. They were used to define a Lagrangian mixing forecast, as well as 48 hour Lagrangian average fields of PV and water vapor mixing ratio and net vertical displacement at 350hPa.

3. GLASH Imagery

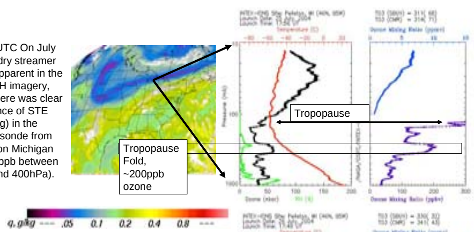
GLASH is a derived product image developed at UVA. It is based on a linearization of the relationship between GOES Imager 6.7 um channel brightness temperature and layer average relative humidity for the upper troposphere. Using the vertical weighting function for the channel along with temperature fields from a meteorological model, images can be "corrected" for temperature and zenith angle biases (Moody et al., 1999). The result is a GOES product that represents layer average specific humidity (GLASH). The GLASH signal is influenced by moisture variations from 250 to 500hPa, with the peak contribution from about 350 hPa. The imagery shows a maximum gradient in moisture along the tropopause break, where dry air on the poleward side of the boundary has a greater contribution from the stratosphere and air on the equatorward side of the gradient represents an largely tropospheric contribution (Wimmers et al., 2003). Animations of this field depict features at a range of scales from synoptic scale ridges and troughs, to finely scaled streamers and rolled vortices, representations of the advective processes that lead to irreversible mixing. Previous work has shown that tropopause folding activity, an important component of STE, is correlated with strong gradients in remotely sensed specific humidity (Wimmers et al., 2004).

4. Results from the INTEX/NA Summer 2004

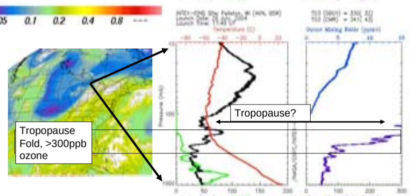
INTEX-NA is an integrated atmospheric field experiment over North America. The programmatic goal is to understand the transport and transformation of gases and aerosols on transcontinental/intercontinental scales and to determine their impact on air quality and climate. Ozone is one of the main constituents of interest, and characterizing STE is relevant to quantifying the tropospheric ozone budget.

Forecasts of upper tropospheric mixing were "validated" by inspection. Regions that were forecast to have large liapunov exponents (mixing), high PV, low water vapor, and subsidence should indicate regions of STE. These forecasts should be realized in the GLASH imagery by strong gradients in upper tropospheric specific humidity that occur along the lengthening boundary between subtropical moist air and dry, ozone-rich polar stratospheric air.

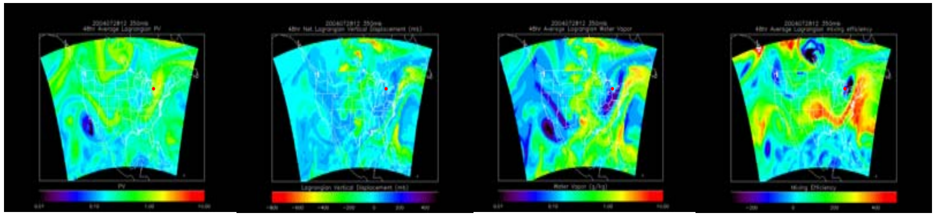
At 18UTC On July 25, a dry streamer was apparent in the GLASH imagery, and there was clear evidence of STE (folding) in the ozonesonde from Pellston Michigan (~200ppb between 300 and 400hPa).



Over the next 24 hours this upper level trough deepened and the sonde over Pellston indicated higher ozone mixing ratios in the upper troposphere.



4. Results from the INTEX/NA Summer 2004, cont.



a) The fold is evident in 350hPa PV >1

b) The fold is evident in 350hPa subsidence > 100mb

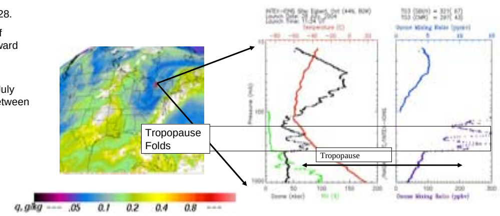
c) The fold is evident in 350hPa wv < 0.1g/kg

d) The fold is evident in 350hPa mixing efficiency > 200 (a measure of the relative magnitude of the Liapunov exponent)

A 48 hour RDF forecast was run from 350hPa validating at 12 UTC on July 28.

It forecast the trough, and the associated dry streamer along with a region of mixing along the boundary of this streamer advecting southward- and -eastward into Ontario, Virginia and N. Alabama.

Clear chemical evidence of STE was present in the ozonesonde at 11UTC, launched from Egbert Ontario (marked in the images as a red asterisk) on July 28, where several layers with ozone mixing ratios ~300 ppb were present between 200 and 400mb.



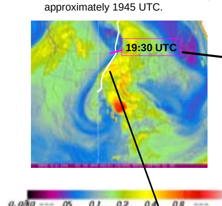
5. TOPSE Example of Upper Tropospheric Mixing Associated with STE

Measurements from TOPSE were used to show that GLASH *gradients* clearly designate the time-varying location of the mid-latitude tropopause break. During the four-month period of TOPSE aircraft flights, every crossing of an upper-tropospheric air mass boundary (observed in the satellite imagery) corresponded in time to a lidar-observed cross-section of tropopause folding (*Wimmers et al.*, 2003). The case on the right is for April 30, 2000. The flight traversed the edge of a streamer with two vortices, one at the northern end and one at the southern end.

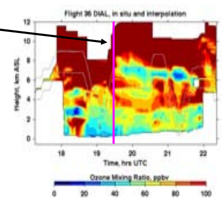
An RDF analysis (using 80km Eta fields) based on 72 hour back trajectories ending at the time of the TOPSE flight (21UTC) shows the streamer and both the vortices (images below). Mixing is enhanced along the path of the flight, however, it is also apparent that over the 72 hour averaging period, there was a considerable amount of mixing present on the *anticyclonic* side of the streamer that has moved off shore.

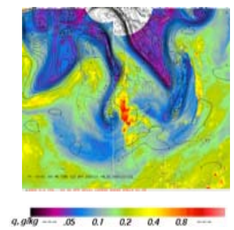
This *downstream feature* is captured better in the larger scale view of the combined GOES East and GOES West GLASH image (see figure to the far right). An overlay of model PV at the time of this image (12UTC April 30) from the Global Forecast System AVN model is shown. The RDF analysis of Liapunov exponents appears to better account for mixing along the persistent boundary between moist and dry air which is featured in GLASH, but not captured in PV.

Flight track (white line) crosses a major gradient in specific humidity (white dashed line) at approximately 1945 UTC.

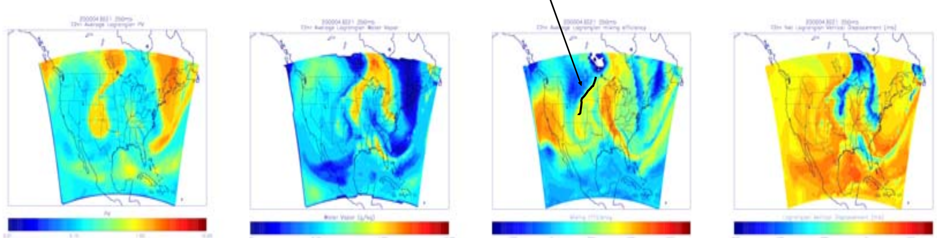


Ozone lidar transect





Flight track



a) The streamer is evident in 350hPa PV >1

b) The streamer is evident in 350hPa wv < 0.1g/kg

c) The fold is evident in 350hPa mixing efficiency > 200 (a measure of the relative magnitude of the Liapunov exponent)

d) The fold is evident in 350mb subsidence > 100mb

6. Conclusions

RDF analyses and forecasts of Lagrangian mixing were compared with gradients in real-time observations of GOES Layer Average Specific Humidity (GLASH), a derived satellite image. Results suggest that these forecasts are useful for predicting mixing associated with STE. Used in conjunction with GLASH imagery, the upper-tropospheric mixing zones are associated with gradients in specific humidity which we have associated with tropopause folding through previous work and with new observations shown here.

The results presented here are very *preliminary and qualitative*, however, they illustrate the potential value of these forecasts. They could be used with future missions, like INTEX-B, in the spring of 2006, to assist flight planning, and to predict and diagnose mixing of stratospheric and tropospheric air in the troposphere.

References

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Acknowledgements

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