Annual Project Report, Year II
Dynamical Analysis of Modeled Ozone Structures in the UTLS over North America
NASA Grant Number: NNX10AG57G
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Goals of Project

We seek to improve our understanding of the dynamics of stratosphere / troposphere exchange (STE) and to improve our capability to model ozone structures in the upper troposphere and lower stratosphere (UTLS). Significant uncertainty exists in our knowledge of dynamical processes associated with STE in the UTLS, especially transport pathways near the subtropical westerly jet. We are comparing ozone data from surface observations, MOZAIC aircraft data, and IONS-06 ozonesondes to ozone structures in Global Earth Observing System (GEOS) simulations and in high resolutions simulations with the University of Wisconsin Non-hydrostatic Modeling System (UWNMS).

Focal questions include:

1) What are typical errors in ozone near tropopause folds and how do they depend on model resolution?
2) How can we improve representation of STE and ozone transport in numerical models?
3) How do transport pathways in the UTLS relate to Rossby wave breaking and baroclinic energetics?
4) What role do inertia-gravity waves and PV streamers play in STE?

The organization of this annual project report is as follows: changes in personnel, new results for Year II, publications, and tasks for Year III.

Changes in Personnel

Dr. Ivanka Stajner was a Co-Investigator on the original proposal, with half of the tasks and funding going to her at Noblis, Inc. During the past year she accepted a permanent civil service job with NOAA and now has different duties and responsibilities. She has agreed to continue collaboration on interpreting results from work on the present grant, on an unfunded basis. In order to carry out the proposed tasks I am using the funds to pay for Research Associate Dr. Marek Rogal to carry out model simulations and comparison with in situ ozone data. We have enjoyed a long working relationship. Dr. Rogal has considerable experience with running the UWNMS with a variety of input data. This grant also supports graduate research assistant Shellie Rowe on the topic of inertial instability and stratosphere –troposphere exchange (STE).

New Results for Year Two

a) Inertial instability and STE

We have carried out four detailed case studies with high resolution UNWMS simulations focusing on weather events over the U.S. on 1) 6 February 2008, 2) 22 April 2005, 3) 22 February 2011, and 4) 3 January 2010. All of these cases reveal strikingly similar local meridional overturning circulations around the westerly jet which are driven by inertial instability and facilitate STE. We have given two public presentations of scientific results at the University of Wisconsin - Madison and are in the process of completing a manuscript for submission to *J. Atmos. Sci.*: *On the influence of inertial instability in stratosphere – troposphere exchange and precipitation maxima in midlatitude cyclones*.

In the process of diagnosing mesoscale numerical weather simulations of strongly banded precipitation events we found that a region of inertially unstable air typically exists in the upper troposphere immediately equatorward of the precipitation maximum. This condition implies that local horizontal wind shear is larger than the Coriolis parameter (local vorticity exceeds planetary vorticity). This condition of inertial instability, hitherto regarded as rare outside of the tropics, further implies that air parcels will accelerate poleward in such regions. A salient feature is the relationship between "tropospheric intrusions" (poleward surges of uppermost tropospheric air over the subtropical westerly jet and the ensuing STE), and regions of negative potential vorticity on the upward and equatorward side of the jet. We have discovered that these regions of inertial instability are indeed intimately linked to layers of upper tropospheric intrusions that surge poleward over the jet into the lower stratosphere, curve downward and then sink back into the troposphere. This provides a dynamical framework for clarifying a fundamental mode of STE.

Four cases have been examined in high resolution simulations with the UWNMS in order to study the dynamics of STE and to investigate transport pathways around the jet. Selected case studies included the storm of February 5-8, 2008, which caused many tornado deaths in the Mississippi and Ohio valleys, while deep snow stranded over 2000 vehicles on I-90 in southern Wisconsin. Figure 1 shows a meridional section in the UWNMS at 0000 UT on February 6, 2008, extending from southern Canada southeastward across Wisconsin to the Atlantic. Purple arrows show the horizontal and vertical winds in the plane of this section perpendicular to the westerly jet, which is located in the center of the picture. Note the moist warm upglide pathway from the south that rises upward in convection on the south side of the jet. Note also the poleward-surging tropospheric intrusion in the uppermost troposphere over the top of the jet. The yellow streamlines in this plane highlight the poleward and downward circulation around the jet shown by the purple arrows. Note the continuous descent of mixed stratospheric / tropospheric intrusion air trending toward the right and down into the troposphere, along the left edge of the region of closed circulation.

This counter-clockwise circulation, which appears closed in this plane, coincides with a region of negative potential vorticity (PV), inside the zero white contour in Fig. 2. Also shown in Fig. 2 are equivalent potential temperature contours in purple. The westerly jet is located where the meridional gradient of potential vorticity is strongest and immediately poleward of the region of negative PV. Indeed, the region of negative PV is due to the strong negative vorticity on the equatorward side of the jet. That is, inertial instability appears to be an essential ingredient in STE near jets.

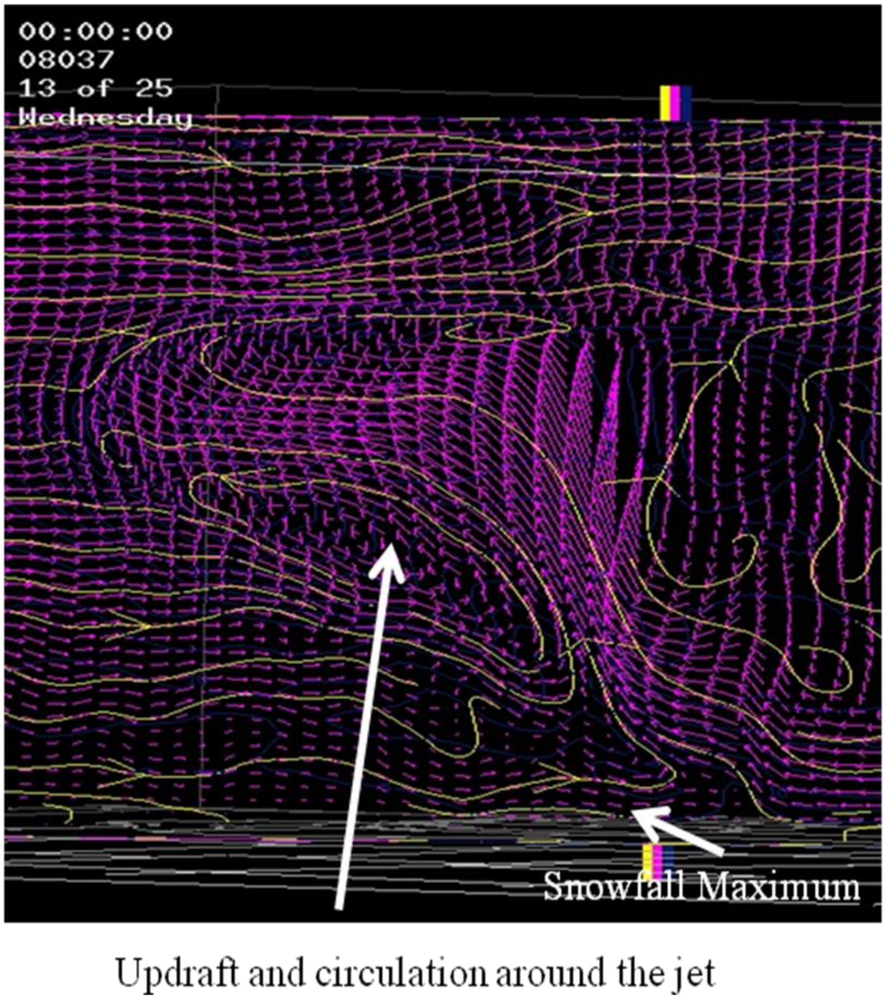

Figure 1. Meridional section in the UWNMS at 0000 UT 6 February, 2008 through a westerly jet showing winds and streamfunction in the plane.

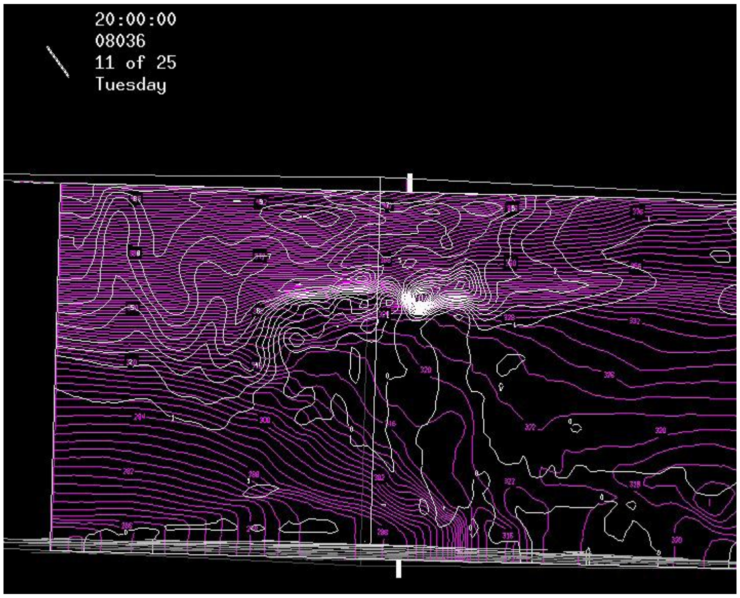

Figure 2. Meridional section in the UWNMS at 2000 UT 5 February, 2008 showing potential vorticity in white and equivalent potential temperature in purple.

The origin of the negative PV is shown in Figure 3 to be in the boundary layer along the convective cold front, where static stability is negative, so PV is negative. The potential for trade-off between convective and inertial instability for negative PV exists because PV is the product of static stability and absolute vorticity.

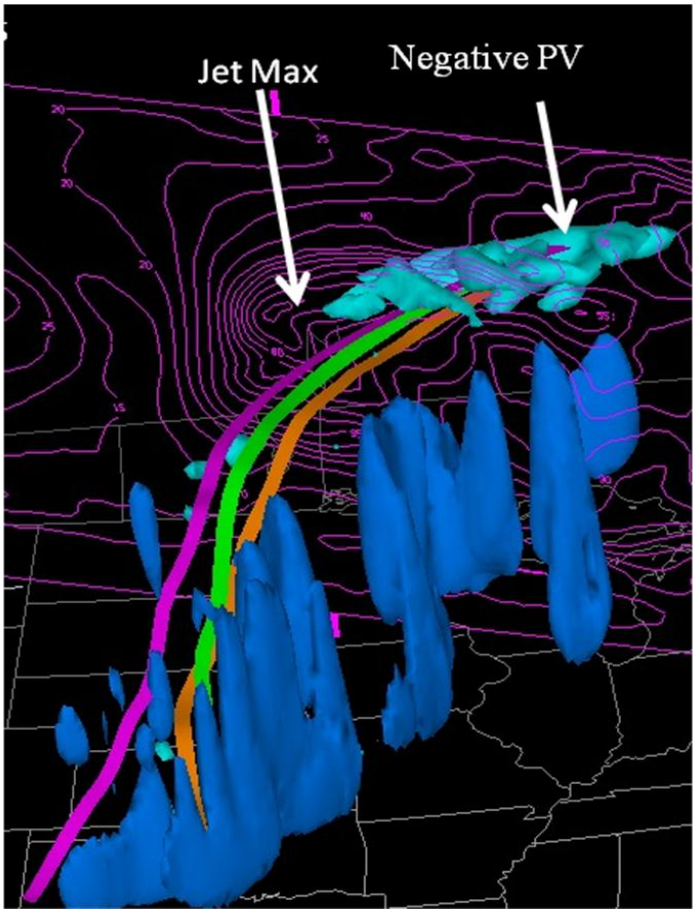

Figure 3. Oblique view of a cross section of the westerly jet core (purple contours) and the negative potential vorticity on its equatorward flank (light blue). Trajectories show that the inertially unstable air has its origins in the boundary layer near the thunderstorms along the cold front (blue turrets are isosurfaces of vertical velocity).

These new perspectives inspire us to re-examine what is known regarding the nature of STE near westerly jets. Midlatitude westerly jets exhibit a downwelling plume on the poleward side characterized by horizontal scales ~100 km (Fig. 1; *Shapiro* 1980). Some attempts to understand this vertical motion pattern have included ageostrophic circulation theories, where the jet entrance / exit quadrupole pattern is required to be consistent with zonal acceleration and deceleration, but this cannot explain the persistent evidence of downwelling air poleward of the jet at almost all longitudes. Here we will focus on the vertical motion field as a primary quantity. Salient questions that we are attempting to address include:

- What is the dynamical cause of the poleward and downward motion near westerly jets?
- What causes the horizontal scale of the downwelling plumes?
- What is the rate of production/destruction of available potential energy (APE)?
- Is a typical circulation bounded by regions of negative potential vorticity?

- What are typical air mass pathways?
- How do transport pathways in the UTLS relate to Rossby wave breaking and baroclinic energetics?
- What role do inertia-gravity waves and PV streamers play in STE?
- How do convective bursts of negative PV relate to mesoscale "flare-ups" in the speed of the jet stream?

This discovery of the relationship between inertial instability, tropospheric intrusions, and stratospheric intrusions provides a compelling integrative dynamical focus studying midlatitude cyclones from a fresh perspective. In our dynamical analysis we will attempt to unify theories of Hadley circulation widths and monsoon circulation widths (cf. *Held and Hou* 1980, *Plumb and Hou* 1992) with uppermost-tropospheric intrusions with the principle that particles will depart from a latitude of inertial neutrality and end up at another latitude of inertial neutrality. This other latitude is a special location, a first-order discontinuity, the tropopause break at the westerly jet. We will further link the downwelling plume to the tropospheric intrusion by exploring the idea that the intrusion "sticks" to the surface of the westerly jet as a turbulent boundary layer, and is thereby re-directed in a downward and eastward spiral around the jet, similar to the Coanda effect in fluid dynamics for flow around a cylinder.

The resulting air motions will be linked to production of available potential energy (APE) in the UTLS. As dense, low-theta upper -tropospheric air subsides at an angle downward and poleward, it can accelerate, as water over a waterfall, and descend poleward of the jet. This "sloping convection" can release some of the APE in the lower stratosphere and amplify the storm through upper level baroclinic instability. The downwelling inertia of this plume extends into the upper troposphere, falling essentially along isentropes, but differential vertical advection can enhance or diminish UT frontogenesis and the generation or release of APE in the UT.

A summary working hypothesis is that low PV air in the uppermost troposphere surges poleward over a westerly jet, sticks to the jet by turbulence, becomes a mixed boundary layer for the jet, and spirals poleward and downward around the jet, with sheets of mixed air penetrating back into the troposphere.

b) Climatology of the stratopause

This work also supported the PI's collaboration on a new description and climatology of the stratopause:

France, J. A., V. L. Harvey, C.E. Randall, M. H. Hitchman, and M. J. Schwartz, 2012: A climatology of stratopause temperature and height. *J. Geophys. Res., in press*.

Multi-year, monthly mean geographic patterns in stratopause temperature and height are shown to depend on the location of the polar vortices and anticyclones. This is the first study to show that the stratopause is, on average, 20 K colder and 5-10 km lower in the Aleutian anticyclone than in ambient air during the Arctic winter. During September in the Antarctic the stratopause is, on average, 10 K colder inside anticyclones south of

Australia. Daily stratopause anomalies can exceed 40 K and 20 km. The climatological structure of the temperature and height anomalies is consistent with moderate baroclinic growth below the stratopause and decay above. This work furthers current understanding of the geography of the stratopause by emphasizing the role of synoptic baroclinic instability, whereby anticyclones establish zonally asymmetric climatological patterns in stratopause temperature and height.

Publications from Year 1

This grant provided partial support for PI Hitchman, Co-I Ivanka Stajner, and one graduate research assistant (RA). The following three publications were supported at least in part by this grant:

Rogal, M., M. H. Hitchman, M. L. Buker, G. J. Tripoli, I. Stajner, and H. Hayashi (2010), Modeling the effects of Southeast Asian monsoon outflow on subtropical anticyclones and midlatitude ozone over the Southern Indian Ocean, *J. Geophys. Res.*, **115**, D20101, doi:10.1029/2009JD012979, 2010.

Wargan, K., S. Pawson, I. Stajner, and V. Thouret (2010), Spatial Structure of Assimilated Ozone in the Upper Troposphere and Lower Stratosphere, *J. Geophys. Res.*, **115**, D24316, doi:10.1029/2010JD013941.

Doughty, D., A. Thompson , M. Schoeberl , I. Stajner , K. Wargan , W. J. Hui (2011), An intercomparison of tropospheric ozone retrievals and measurements in western North America in 2006 derived from two Aura instruments, *J. Geophys. Res.*, in press.

Rogal et al. (2010) showed that GEOS ozone data is quite useful in depicting STE associated with breaking Rossby waves in the Southern Hemisphere. They showed that anomalously high ozone amounts are found in the UTLS on the poleward side of subtropical anticyclones associated with deep tropical convective outflow pulses in the UTLS.

Assimilated GEOS ozone data (*Stajner et al*., 2008) from the Microwave Limb Sounder (MLS) and Ozone Monitoring Instrument (OMI) was compared against independent in-situ ozone measurements. The comparisons included data from ozonesondes from the Intercontinental Chemical Transport Experiment (INTEX) Ozonesonde Network Study (IONS-06) and aircraft measurements from Measurements of OZone, water vapour, carbon monoxide and nitrogen oxides by in-service AIrbus aircraft (MOZAIC). Assimilated MLS and OMI ozone reproduces major features of IONS-06 profiles in the UTLS, including the high ozone variability during spring months and a transition to lower ozone variability during summer months.

Wargan et al. (2010) compared GEOS assimilated ozone data with MOZAIC data along aircraft cruising altitudes in the UTLS and determined that the model, rather than the satellite data, determines the representation of smaller spatial scales. This provides further motivation for the present study of STE using finer resolution regional models.

Doughty et al. (2011) focused on the representation of ozone profiles, their vertical resolution and error correlations over western North America. Comparisons with MOZAIC used data from the ascent and descent phases of the flights. Comparisons with ozonesondes used IONS-06 data. *Doughty et al*. found excellent agreement for tropospheric ozone columns, although there are cancelling biases in the upper and lower parts of profiles. Two ozone profile cases with larger discrepancies were identified, with indications that complex dynamics or an inaccurate representation of the dynamics contributes to discrepancies. This study further motivates using finer resolution regional models.

Tasks for Year 3

We will write another paper on inertial instability and STE, in addition to the case study paper, which emphasizes theoretical interpretation. This work provides a newly-focused dynamical understanding for a crucial mixing process which must be modeled accurately in order to represent trace constituent distributions well.

With Dr. Rogal now working on the project we will greatly accelerate our efforts in comparing modeled and observed ozone structures. We have identified six case studies of interesting discrepancies between local ozonesonde profiles and assimilated ozone structure. We will obtain ACE satellite data and AIRS data and begin analysis . We will focus on our dynamical questions listed above. The fundamental idea is to integrate air mass pathways with types of Rossby wave breaking to study tropospheric intrusions into the stratosphere. These typically take the form of low PV air mass near 380-390 K in the tropical UTLS sliding poleward over the subtropical westerly jet, overlying higher PV air in the extratropical stratosphere near 350 K. Such folds seen over the U.S. often begin over the far western Pacific. We will investigate the synoptic/dynamic nature of how these "tropospheric intrusions" begin and how they mix with stratospheric air and re-enter the troposphere by running nested grid simulations with the UWNMS using GEOS 2006 boundary conditions for the following cases of interesting ozone profile disagreement between GEOS and in situ data:

1) Trinidad Head CA, April 18-22, 2006
2) Kelowna, BC, March 15, 2006
3) Trinidad Head, May 2, 2006
4) Table Mountain, August 1, 2006.

We will also carry out simulations with the UWNMS using GFS boundary conditions for the following cases in the literature which focus on tropospheric intrusions over the Pacific:

5) RF01 for START08, April 4-16, 2008

6) RF14 for START08, June 11-18, 2008.

The larger domain at 40 km x 40 km x 300 m will extend across the Pacific, while the smaller grid at 4 km x 4 km x 300 m will focus on the details of the incipient folds. We will use the Langley trajectory code to track air masses. We seek a more complete synoptic/dynamic description of the origin and evolution of tropospheric intrusions.

Budget request for Year III

The requested budget of $167K includes partial salaries for the PI, one 50% graduate research assistant, one 100% research associate, publications and travel to two meetings.

References cited:

Held, I. M., and A. Y. Hou, 1980: Nonlinear axisymmetric circulations in a nearly inviscid atmosphere. *J. Atmos. Sci*., **37**, 515-533.

Plumb, R. A., and A. Y. Hou, 1992: The response of a zonally symmetric atmosphere to subtropical thermal forcing: Threshold behavior. *J. Atmos. Sci*., **49**, 1790-1799.

Shapiro, M. A., 1980: Turbulent mixing within tropopause folds as a mechanism for the exchange of chemical constituents between the stratosphere and troposphere. *J. Atmos. Sci*., **37**, 994-1004.

Stajner, I., K. Wargan, S. Pawson, H. Hayashi, L.-P. Chang, R. C. Hudman, L. Froidevaux, N. Livesey, P. F. Levelt, A. M. Thompson, D. W. Tarasick, R. Stübi, S. B. Andersen, M. Yela, G. König-Langlo, F. J. Schmidlin, and J. C. Witte (2008), Assimilated Ozone from EOS-Aura: Evaluation of the Tropopause Region and Tropospheric Columns, *J. Geophys. Res.,* **113**, D16S32, doi:10.1029/2007JD008863.