Title of Grant / Cooperative Agreement:	Dynamical Analysis of Modeled Ozone Structures in the UTLS over North America
Type of Report:	Summary of Research
Name of Principal Investigator:	Matthew H. Hitchman
Period Covered by Report:	April 1, 2010 - March 31, 2014
Name and Address of recipient's institution:	University of Wisconsin System, 21 N. Park St. Ste 6401, Madison, WI 53715-1218
NASA Grant / Cooperative Agreement Number:	NNX10AG57G

Reference 14 CFR § 1260.28 Patent Rights *(abbreviated below)*
The Recipient shall include a list of any Subject Inventions required to be disclosed during the preceding year in the performance report, technical report, or renewal proposal. A complete list (or a negative statement) for the entire award period shall be included in the summary of research.

Subject inventions include any new process, machine, manufacture, or composition of matter, including software, and improvements to, or new applications of, existing processes, machines, manufactures, and compositions of matter, including software.

Have any Subject Inventions / New Technology Items resulted from work performed under this Grant / Cooperative Agreement?	No ●	Yes ○
If yes a complete listing should be provided here: Details can be provided in the body of the Summary of Research report.		

Reference 14 CFR § 1260.27 Equipment and Other Property (abbreviated below)
A Final Inventory Report of Federally Owned Property, including equipment where title was taken by the Government, will be submitted by the Recipient no later than 60 days after the expiration date of the grant. Negative responses for Final Inventory Reports are required.

Is there any Federally Owned Property, either Government Furnished or Grantee Acquired, in the custody of the Recipient?	No ●	Yes ○
If yes please attach a complete listing including information as set forth at § 1260.134(f)(1).		

Attach the Summary of Research text behind this cover sheet.

Reference 14 CFR § 1260.22 Technical publications and reports (December 2003)
Reports shall be in the English language, informal in nature, and ordinarily not exceed three pages (not counting bibliographies, abstracts, and lists of other media).

A Summary of Research (or Educational Activity Report in the case of Education Grants) is due within 90 days after the expiration date of the grant, regardless of whether or not support is continued under another grant. This report shall be a comprehensive summary of significant accomplishments during the duration of the grant.

Final Project Report
Dynamical Analysis of Modeled Ozone Structures in the UTLS over North America
NASA Grant Number: NNX10AG57G
PI: Prof. Matthew H. Hitchman, University of Wisconsin - Madison

Goals of Project

The primary goals were to improve 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 uncertainties exist in our knowledge of dynamical processes associated with STE in the UTLS, especially transport pathways near the subtropical westerly jet. Our original plan was to compare 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).

However, in year two of the grant there was a major change in personnel. Dr. Ivanka Stajner was Co-Investigator on the original proposal, with half of the tasks and funding going to her at Noblis, Inc. Then she accepted a permanent civil service job with NOAA and acquired different duties and responsibilities. In order to carry out the proposed tasks I used the funds to pay salaries for Research Associate Dr. Marek Rogal and graduate research assistant Shellie Rowe. In the final year of the project Dr. Rogal was offered a permanent position in the Space Science and Engineering Center at Madison. Ms. Rowe completed her M.S. thesis on the topic of inertial instability and stratosphere – troposphere exchange (STE). Her unique work has led to two new manuscripts and several new research avenues.

Publications supported at least in part by this grant:

1) 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.

GEOS ozone data is quite useful in depicting STE associated with breaking Rossby waves in the Southern Hemisphere. 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.

2) 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.

This paper 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.

3) Doughty, D. C., A. M. Thompson, M. R. Schoeberl, I. Stajner, K. Wargan, and W. C. J. Hui, 2011: An intercomparison of tropospheric ozone retrievals derived from two Aura instruments and measurements in western North America in 2006, *J. Geophys. Res.*, **116**, D06303, doi:10.1029/2010JD014703.

This work 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. They 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.

4) France, J. A., V. L. Harvey, C. E. Randall, M. H. Hitchman, and M. J. Schwartz , 2012: A climatology of stratopause temperature and height in the polar vortex and anticyclones, *J. Geophys. Res.*, **117**, D06116, doi:10.1029/2011JD016893.

Multi-year, monthly mean geographic patterns in stratopause temperature and height were 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.

5) Rowe, Shellie M., 2014: *On the Role of Inertial Instability in Stratosphere-Troposphere Exchange and the Generation of Inertial Flare-Ups Near Midlatitude Jets*, 130 pp., M.S. thesis, University of Wisconsin - Madison.

6) Rowe, S. M., and M. H. Hitchman, 2014: On the role of inertial instability in stratosphere troposphere exchange in midlatitude cyclones, *submitted to J. Atmos. Sci.*

7) Hitchman, M. H., S. M. Rowe, and G. J. Tripoli, 2014: A momentum surge view of tropopause folds, *to be submitted to J. Atmos. Sci.*

Inertial instability and STE

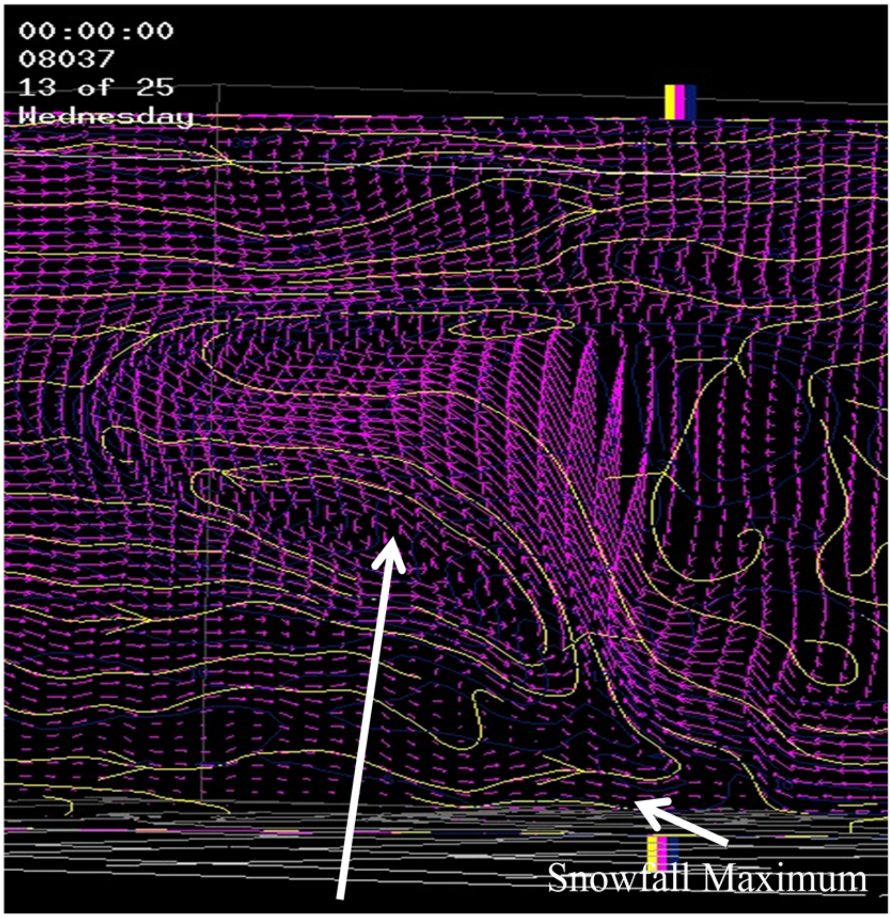
We have carried out more than ten detailed case studies with high resolution UNWMS simulations wherein inertial instability occurred in the UTLS near westerly jets and midlatitude cyclones. Publication 6) focuses on weather events over the U.S. on 1) 6

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.

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.

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.

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 a contributing and significant ingredient in STE near jets.



Updraft and circulation around the jet

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

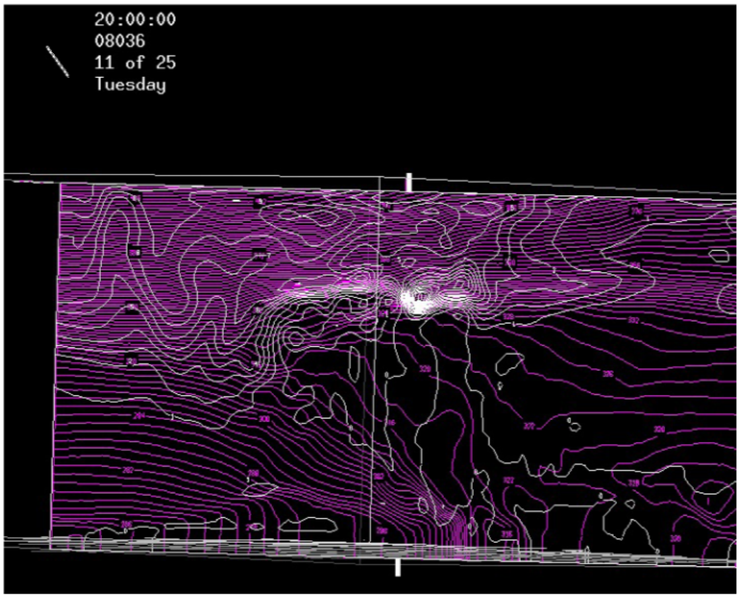


Figure 2. Meridional section in the UWNMS at 2000 UT 5 February, 2008 showing potential vorticity in white and equivalent potential temperature in purple.

The origin of the negative PV is shown in Figure 3 to be in the boundary layer along the convective cold front, where PV is negative.

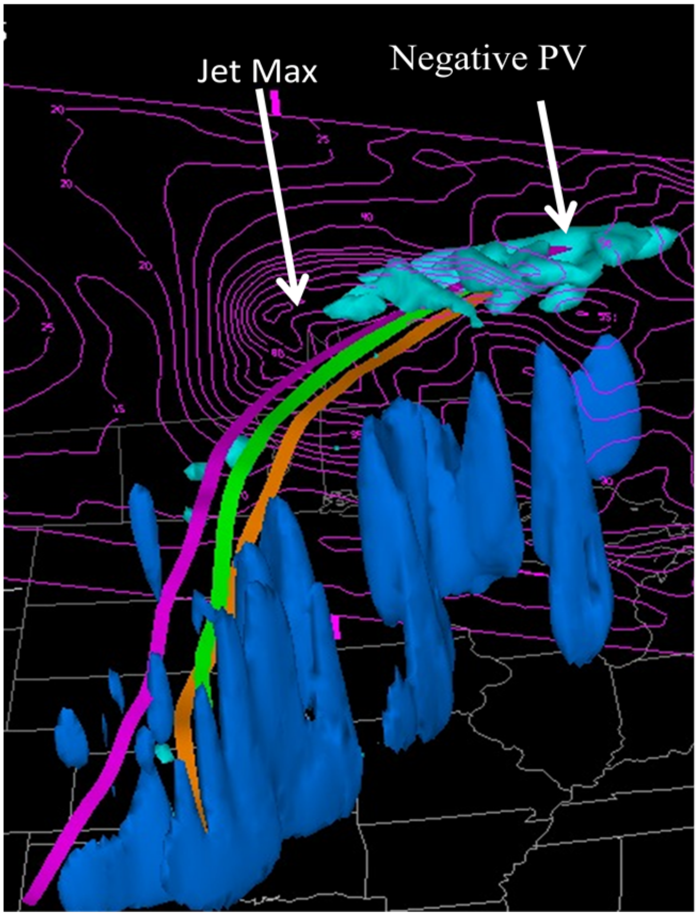


Figure 3. Oblique view of a cross section of the westerly jet core (purple contours) and the negative potential vorticity on its equatorward flank (light blue). Trajectories show that the inertially unstable air has its origins in the boundary layer near the thunderstorms along the cold front (blue turrets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

These new perspectives inspired 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. Manuscript 7) attempts to address the following questions: What is the dynamical cause of the poleward and downward motion near westerly jets? What causes the horizontal scale of the downwelling plumes? How do transport pathways in the UTLS relate to Rossby wave breaking and baroclinic energetics?

Other manuscripts in preparation will attempt to address the following: How do convective bursts of negative PV relate to mesoscale “flare-ups” in the speed of the jet stream? How does STE around the periphery of tropical cyclones influence their evolution?

Public Presentations by Matthew Hitchman:

December 17, 2011, M. H. Hitchman, "Influence of Tropical Convection on the Distribution of Ozone in the Southern Hemisphere During the Winter to Spring Transition", poster at the Fall AGU meeting in San Francisco.

February 10, 2011, M. H. Hitchman, "Tropical / Extratropical Interaction in the UTLS", Workshop on Winds from International Space Station Lidar, Miami, FL.

June 10-15, 2011, M. H. Hitchman, Presented three invited lectures on the dynamics of the stratosphere at the first Canadian summer school on arctic climate change in Nottawasaga, Ontario.

October 14, 2011, M. H. Hitchman, "The Spring 2011 Northern Hemisphere Ozone Hole", Madison, WI.

October 21, 2011, M. H. Hitchman, "The Spring 2011 Southern Hemisphere Ozone Hole", Madison WI.

November 2, 2011, M. H. Hitchman, "Tropical Forcing of the Southern Hemisphere: ENSO, Climate Change, and Jet Migration", AOS Department Seminar, Madison, WI.

January 30, 2012, M. H. Hitchman, "Volcanic Eruptions, the Quasibiennial Oscillation and the General Circulation", Departmental Colloquium, Madison, WI.

November 26, 2012, M. H. Hitchman,, "The 2012 Antarctic Ozone Hole", Madison, WI.

April 2, 2013, M. H. Hitchman, "Seasonal and ENSO Influence of Tropical Convection on SH Ozone Distribution", WCRP Workshop on Stratosphere and Troposphere Coupling and Climate Change, Kyoto University, Japan.

June 12, 2013, Invited talk, M. H. Hitchman, "Transport into the stratosphere via the summer Asian high", Workshop on Atmospheric Composition and the Asian Summer Monsoon (ACAM), Kathmandu, Nepal.

June 19, 2013, M. H. Hitchman, Oral presentation, "Sensitivity of Southern Hemisphere Circulation to Tropical Convective Forcing: Modulation of Polar Regions via Planetary Wave Trains in the UTLS", 17th Conference on the Middle Atmosphere, Newport, Rhode Island.

June 19, 2013, S. M. Rowe and M. H. Hitchman, "On the role of inertial instability in stratosphere troposphere exchange near midlatitude cyclones", 17th Conference on the Middle Atmosphere, Newport, Rhode Island.

September 16, 2013, M. H. Hitchman, "Transport into the stratosphere via the Tibetan High", AOS Department Colloquium, Madison, WI.

May 2, 2014, T. Kinoshita, K. Sato, and M. H. Hitchman, co-author on poster "Three dimensional structure of planetary wave activity from tropical to extratropical regions in ENSO", Geoscience Union Meeting, Yokohama.

Public Presentations by Shellie Rowe**:**

4th Annual AOSS Poster Reception, May 2014, Union South, Madison, WI: The Significance of Inertial Instability on Meridional Circulation Patterns Along the Midlatitude Westerly Jet.

8th Annual Nelson Institute Earth Day Conference, April 2014, Monona Terrace, Madison, WI: On the Role of Inertial Instability in the Generation of Inertial Flare-Ups in Midlatitude Westerly Jets.

AMS 17th Conference on the Middle Atmosphere, June 2013, Newport, RI: The Role of Inertial Instability in Stratosphere-Troposphere Exchange in Midlatitude Cyclones.

3rd Annual AOSS Poster Reception, May 2013, Union South, Madison, WI: On the Role of Inertial Instability in the Generation of Inertial Flare-Ups in Midlatitude Westerly Jets.

7th Annual Nelson Institute Earth Day Conference, April 2013, Monona Terrace, Madison, WI: The Role of Inertial Instability in Stratosphere-Troposphere Exchange in Midlatitude and Tropical Cyclones.

AOS Department Seminar, UW-Madison, March 2013: The Role of Inertial Instability in Stratosphere-Troposphere Exchange and the Generation of Inertial Flare-Ups Near Midlatitude Cyclones.

AOS Department Seminar, UW-Madison, November: The Influence of Inertial Instability in Stratosphere-Troposphere Exchange and Mesoscale Precipitation Maxima in Mid-latitude Cyclones.

References cited:

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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.