REPORT DOCUMENTATION PAGE

Form Approved OMB NO. 0704-0188

1. REPORT DATE (DD-MM-YYYY)	2. REPORT TYPE	3. DATES COVERED (From - To)
20-03-2017	Final Report	1-Dec-2008 - 31-May-2013

4. TITLE AND SUBTITLE
Final Report: Further implementation and refinement of the QNSE model of turbulence

5a. CONTRACT NUMBER
W911NF-09-1-0018

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
622120

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

6. AUTHORS
Boris Galperin

7. PERFORMING ORGANIZATION NAMES AND ADDRESSES
University of South Florida
3650 Spectrum Blvd
Suite 160
Tampa, FL 33612 -9446

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS (ES)
U.S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSOR/MONITOR'S ACRONYM(S)
ARO

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
53385-EV.21

12. DISTRIBUTION AVAILIBILITY STATEMENT
Approved for Public Release; Distribution Unlimited

13. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not contrued as an official Department of the Army position, policy or decision, unless so designated by other documentation.

14. ABSTRACT
QNSE theory of stably stratified turbulence was used to derive an analytical transition from the Kolmogorov to stratified subranges. The QNSE formulation was combined with EDMF to develop a model suitable for both stable and unstable stratification. This hybrid model was tested in WRF. This effort was a subject of a PhD dissertation that was successfully defended. Analytical and experimental methods were used to develop a theory of anisotropic turbulence with Rossby waves and potential vorticity monotonizing. A regime of zonostrophic turbulence discovered in our previous research was found to exist in the atmosphere of Jupiter. This result was based upon the

15. SUBJECT TERMS
QNSE theory of turbulence, atmospheric boundary layers, EDMF methods, Rossby waves

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	15. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
UU	UU	UU	UU		Boris Galperin
					19b. TELEPHONE NUMBER
					727-553-1249

Report Title

Final Report: Further implementation and refinement of the QNSE model of turbulence

ABSTRACT

QNSE theory of stably stratified turbulence was used to derive an analytical transition from the Kolmogorov to stratified subranges. The QNSE formulation was combined with EDMF to develop a model suitable for both stable and unstable stratification. This hybrid model was tested in WRF. This effort was a subject of a PhD dissertation that was successfully defended. Analytical and experimental methods were used to develop a theory of anisotropic turbulence with Rossby waves and potential vorticity monotonizing. A regime of zonostrophic turbulence discovered in our previous research was found to exist in the atmosphere of Jupiter. This result was based upon the observational data collected by the Cassini spaceship. Generally, we have made a significant progress in understanding and quantification of anisotropic turbulence on both small and large scales.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
01/23/2017	13	Semion Sukoriansky, Boris Galperin. QNSE theory of turbulence anisotropization and onset of the inverse energy cascade by solid body rotation, Journal of Fluid Mechanics, ( ): 384. doi:
01/23/2017	8	Esa-Matti Tastula, Boris Galperin, Semion Sukoriansky, Ashok Luhar, Phil Anderson. The importance of surface layer parameterization in modeling of stable atmospheric boundary layers, Atmospheric Science Letters, ( ): 83. doi:
01/23/2017	12	Esa-Matti Tastula, Margaret A. LeMone, Jimy Dudhia, Boris Galperin. The impact of the QNSE-EDMF scheme and its modifications on boundary layer parameterization in WRF: modelling of CASES-97, Quarterly Journal of the Royal Meteorological Society, ( ): 1182. doi:
01/23/2017	11	Esa-Matti Tastula, Boris Galperin, Jimy Dudhia, Margaret A. LeMone, Semion Sukoriansky, Timo Vihma. Methodical assessment of the differences between the QNSE and MYJ PBL schemes for stable conditions, Quarterly Journal of the Royal Meteorological Society, ( ): 2077. doi:
01/23/2017	9	Boris Galperin, Jesse Hoemann, Stefania Espa, Gabriella Di Nitto, Guglielmo Lacorata. Anisotropic macroturbulence and diffusion associated with a westward zonal jet: From laboratory to planetary atmospheres and oceans, Physical Review E, ( ): 1. doi:
03/13/2017	4	Arakel Petrosyan, Boris Galperin, Soren E. Larsen, Stephen R. Lewis, Anni Määttänen, Peter L. Read, Nilton Renno, L. Peter H. T. Rogberg, Hannu Savijärvi, Tero Siili, Aymeric Spiga, Anthony Toigo, and Louis Vázquez. THE MARTIAN ATMOSPHERIC BOUNDARY LAYER, Reviews of Geophysics, (05 2011): 1. doi:
03/13/2017	14	Boris Galperin, Jesse Hoemann, Stefania Espa, Gabriella Di Nitto. Anisotropic turbulence and Rossby waves in an easterly jet: An experimental study, Geophysical Research Letters, ( ): 6237. doi:
03/14/2017	1	Semion Sukoriansky, Boris Galperin. An Analytical Theory of the Buoyancy - Kolmogorov Subrange Transition in Turbulent Flows with Stable Stratification, Philosophical Transactions of the Royal Society A, (03 2011): 1. doi:
03/14/2017	20	Esa-Matti Tastula, Timo Vihma, Edgar L. Andreas, Boris Galperin. Validation of the diurnal cycles in atmospheric reanalyses over Antarctic sea ice, Journal of Geophysical Research: Atmospheres, ( ): 4194. doi:
03/14/2017	18	Jielun Sun, Carmen J. Nappo, Larry Mahrt, Danijel Belušic, Branko Grisogono, David R. Stauffer, Manuel Pulido, Chantal Staquet8, Qingfang Jiang9, Annick Pouquet, Carlos Yagüe, Boris Galperin, Ronald B. Smith, John J. Finnigan, Shane D. Mayor, Gunilla Svensson, Andrey A. Grachev, William D. Neff. Review of wave-turbulence interactions in the stable atmospheric boundary layer, Reviews of Geophysics, ( ): 1. doi:
03/14/2017	19	Esa-Matti Tastula, Timo Vihma, Edgar L Andreas. Evaluation of Polar WRF from Modeling the Atmospheric Boundary Layer over Antarctic Sea Ice in Autumn and Winter, Monthly Weather Review, ( ): 3919. doi:

03/14/2017	17	Boris Galperin, Roland M.B. Young, Semion Sukoriansky, Nadejda Dikovskaya, Peter L. Read, Andrew J. Lancaster, David Armstrong. Cassini observations reveal a regime of zonostrophic macroturbulence on Jupiter, Icarus, ( ): 295. doi:
03/20/2017	22	Semion Sukoriansky, Nadejda Dikovskaya, Boris Galperin. Transport of momentum and scalar in turbulent flows with anisotropic dispersive waves, Geophysical Research Letters, ( ): 1. doi:

TOTAL: **13**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

1. Galperin, B., S. Sukoriansky, N. Dikovskaya, R.M.B. Young, P.L. Read, A.J. Lancaster, and D. Armstrong, Zonostrophic macroturbulence and flow energetics on Jupiter from Cassini data. Weizmann Institute of Science, Rehovot, Israel, August 14, 2013.

2. Galperin, B., S. Sukoriansky, N. Dikovskaya, R.M.B. Young, P.L. Read, A.J. Lancaster, and D. Armstrong, The Regime of Zonostrophic Macroturbulence and Its Application for Characterization of Large-Scale Circulation on Jupiter and Other Giant Planets. Crossing the Boundaries in Planetary Atmospheres: From Earth to Exoplanets. The AGU Chapman Conference, Annapolis, MD, June 24-28, 2013.

3. Galperin, B. Zonal jets and eddies – planetary science and satellite oceanography at the crossroads – Second meeting. International Space Science Institute, Bern, Switzerland, April 2, 2013.

4. Galperin, B., S. Sukoriansky, N. Dikovskaya, R.M.B. Young, P.L. Read, A.J. Lancaster, and D. Armstrong, Macroturbulence on Jupiter as emerging from Cassini data. Geostrophic Turbulence and Active Tracer Transport in 2 Dimensions, Princeton Center for Theoretical Science, Princeton University, March 13-15, 2013.

5. Galperin, B., S. Sukoriansky, QNSE theory of anisotropic turbulence and dispersive waves in stably stratified atmosphere and oceans. Wave-Turbulence Interactions in Stable Atmospheric Boundary Layers (WINABL), July 23-27, 2012. National Center for Atmospheric Research, Boulder, Colorado.

6. Galperin, B., S. Sukoriansky, N. Dikovskaya, Rossby waves and zonons in zonostrophic turbulence. British Applied Mathematics Colloquium, 28 March, 2012.

7. Galperin, B., Zonal jets and eddies – planetary science and satellite oceanography at the crossroads. International Space Science Institute, Bern, Switzerland, March 5, 2012.

8. Galperin, B., S. Sukoriansky, N. Dikovskaya, Mean flows and waves in beta-plane turbulence. 2012 Ocean Sciences Meeting, Salt Lake City, 23 February 2012.

9. Galperin, B., S. Sukoriansky, N. Dikovskaya, Rossby waves and solitary waves (zonons) in beta-plane turbulence. Rotating Fluids 2012. University College London, 6 January 2012.

10. Galperin, B., S. Sukoriansky, N. Dikovskaya, Rossby waves and solitary waves (zonons) in beta-plane turbulence. AGU Fall Meeting 2011. San-Francisco, December 8, 2011.

11. Galperin, B., S. Sukoriansky, N. Dikovskaya, Rossby waves and zonons in zonostrophic turbulence. Atmospheric, Oceanic and Planetary Physics, University of Oxford, November 25, 2011.

12. Galperin, B., S. Sukoriansky. An analytical theory of the Kolmogorov-buoyancy subrange transition in stably stratified turbulent flows. Turbulent Mixing and Beyond, Third International Conference The Abdus Salam International Centre for Theoretical Physics. Strada Costiera 11, 34014 Trieste, Italy, 21 - 28 August, 2011.

13. Galperin, B., S. Sukoriansky, J. Pergaud, Hybrid QNSE-EDKF model of PBL in WRF. NWP Workshop on Model Physics with an Emphasis on Short-Range Prediction, Washington D.C., July 26-28, 2011.

14. Galperin, B., S. Sukoriansky, N. Dikovskaya, Zonostrophic turbulence, zonal jets and mixing barriers. 2011 Program of Study in Geophysical Fluid Dynamics Woods Hole Oceanographic Institution Woods Hole, 18 July 2011.

15. Galperin, B., S. Sukoriansky. An analytical theory of the Kolmogorov-buoyancy subrange transition in stably stratified turbulent flows. Department of Civil and Environmental Engineering DICEA, Sapienza Università di Roma, Italy. 5 July 2011.

16. Galperin, B., S. Sukoriansky, N. Dikovskaya, Zonostrophic turbulence, zonal jets and mixing barriers. Department of Civil and Environmental Engineering DICEA, Sapienza Università di Roma, Italy, 4 July 2011.

17. Sukoriansky, S., N. Dikovskaya, B. Galperin, Nonlinear waves (zonons) in zonostrophic turbulence. Waves and instabilities in space and astrophysical plasmas. Eilat, June 19-24, 2011.

18. Galperin, B., S. Sukoriansky. An analytical theory of the Kolmogorov-buoyancy subrange transition in stably stratified turbulent flows. Imperial College, London. 16 June 2011.

19. Galperin, B., S. Sukoriansky. An analytical theory of the Kolmogorov-buoyancy subrange transition in stably stratified turbulent flows. Wave-flow interactions A network in mathematics: fourth meeting. Cambridge University, 11-15 April 2011.

20. Galperin, B., S. Sukoriansky, N. Dikovskaya, Zonostrophic turbulence, zonal jets and the mixing barriers. Department of Meteorology, University of Reading, Reading, UK, 6 January 2011.

21. Galperin, B., S. Sukoriansky, N. Dikovskaya, Zonostrophic turbulence, zonal jets and the mixing barriers. Faculty of Engineering, Tel-Aviv University, 19 December 2010.

22. Galperin, B., S. Sukoriansky, Turbulence-wave interaction in flows with stable stratification: spectral viewpoint. Topographic internal waves in the atmosphere and ocean Cargèse (Corsica), France, November 2-11, 2010.

23. Galperin, B., S. Sukoriansky, N. Dikovskaya, Zonostrophic turbulence, zonal jets and the mixing barriers. RSMAS, University of Miami, 15 October 2010.

24. Galperin, B., S. Sukoriansky, J. Pergaud, Current state of QNSE PBL model in WRF. The Third International Workshop on Next-Generation NWP Models. 29 August –1 September 2010, Jeju Island, Korea.

25. Galperin, B., S. Sukoriansky, Diffusion of momentum and scalar in anisotropic 2D and 3D turbulence with dispersive waves. Wave-flow interactions. A network in mathematics: third meeting. University of St Andrews, 14-18 June 2010.

26. Galperin, B., S. Sukoriansky, Zonal jets and nonlinear waves in turbulence with a beta-effect. Laboratoire de Météorologie Dynamique Ecole Normale Supérieure Paris, France, June 30, 2010.

27. Galperin, B., S. Sukoriansky, Zonal jets and nonlinear waves in turbulence with a beta-effect. National Oceanography Centre, University of Southampton, March 10, 2010, UK.

28. Galperin, B., S. Sukoriansky, Transport of momentum and scalars in anisotropic turbulence with dispersive waves. 2010 Ocean Sciences Meeting, 22-26 February 2010, Portland, Oregon.

29. Galperin, B., S. Sukoriansky, Turbulent transport of momentum and scalars in geophysical flows. Department of Mathematics, Imperial College London, January 26, 2010, UK.

30. Galperin, B., S. Sukoriansky, Turbulent transport of momentum and scalars in geophysical flows. Department of Applied Mathematics and Theoretical Physics, University of Cambridge, Cambridge, December 21, 2009, UK.

31. Galperin, B., S. Sukoriansky, Turbulent transport processes in atmospheres and oceans. Department of Atmospheric, Oceanic and Planetary Physics, Oxford University, Oxford, November 19, 2009, UK.

32. Galperin, B., S. Sukoriansky, Turbulent transport of momentum and scalars in geophysical flows. Ocean-Atmosphere Energy Transport Conference, Caltech, November 5-7, 2009, Pasadena, California.

33. Galperin, B., S. Sukoriansky, Modeling of turbulent transfer of momentum and scalars in geophysical flows. NRL – Stennis Space Center, October 28, 2009, Mississippi.

34. Galperin, B., S. Sukoriansky, and N. Dikovskaya, Turbulent diffusion of momentum and scalar in flows with internal and Rossby waves. 9th EMS Annual Meeting, 28 September – 02 October, 2009, Meteo France, Toulouse, France.

35. Sukoriansky, S., B. Galperin, and N. Dikovskaya, Turbulent transport and waves in zonostrophic turbulence, EUROMECH European Turbulence Conference ETC12, Marburg, September 2009, Germany.

36. Galperin, B., S. Sukoriansky, Transport of momentum and tracers in the turbulent ocean. National Oceanography Centre, Southampton, August 5, 2009, UK.

37. Galperin, B., S. Sukoriansky, Large-scale and small-scale mixing in turbulence with anisotropic dispersive waves. National Institute of Biology, Piran, Slovenia, July 29, 2009.

38. Galperin, B., S. Sukoriansky, Anisotropic large-scale circulation and transport in zonostrophic turbulence, Tutorial. Turbulent Mixing and Beyond. International Conference and Advanced School The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy, 27 July - 07 August, 2009.

39. Sukoriansky, S., and B. Galperin, A quasi-normal theory of turbulence and its applications in geophysical fluid dynamics, Tutorial. Turbulent Mixing and Beyond. International Conference and Advanced School The Abdus Salam International Centre for Theoretical Physics, Trieste, Italy, 27 July - 07 August, 2009.

40. Galperin, B., S. Sukoriansky, and A. Grantinger, Verification of the QNSE turbulence model in WRF. WRF PBL working group meeting, June 23, 2009, NCAR, Boulder, Colorado.

41. Galperin, B., and S. Sukoriansky, Large-scale and small-scale mixing in turbulence with anisotropic dispersive waves. Physical Oceanography Review Symposium, June 9, 2009, Chicago, IL.

42. Galperin, B., and S. Sukoriansky, Transport of momentum and scalar in turbulent flows with anisotropic dispersive waves. Wave-flow interactions, E-Science Institute, University of Edinburgh, Edinburgh, UK, May 26, 2009.

43.Galperin, B., and S. Sukoriansky, Transport of momentum and scalar in turbulent flows with anisotropic dispersive waves. The Technion – Israel Institute of Technology, May 18, 2009, Haifa, Israel.

44. Galperin, B., and S. Sukoriansky, Transport of momentum and scalar in turbulent flows with anisotropic dispersive waves. University College London, April 27, 2009, London, England.

45. Galperin, B., and S. Sukoriansky, A quasi-normal scale elimination (QNSE) theory of stably stratified turbulence. Invited presentation at the Workshop on Modeling the Ocean: Dynamics, Syntheses & Predictions. February 23-26, 2009, Taipei, Taiwan.

46. Galperin, B., S. Sukoriansky, and N. Dikovskaya, Nonlinear waves (zonons) in zonostrophic turbulence. Invited presentation at the Workshop on Modeling the Ocean: Dynamics, Syntheses & Predictions. February 23-26, 2009, Taipei, Taiwan.

47. Galperin, B., and S. Sukoriansky. Advanced parameterization and modeling of turbulent atmospheric boundary layers. Army Atmospheric Sciences Overview Rayleigh-Durham, NC, February 4, 2009.

Number of Presentations: 47.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u> <u>Paper</u>

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

<u>Received</u> <u>Paper</u>

03/14/2017 6.00 Semion Sukoriansky, Nadejda Dikovskaya, Roger Grimshaw, Boris Galperin. Rossby waves and zonons in zonostrophic turbulence,
Waves and Instabilities in Space and Astrophysical Plasmas. 20-SEP-11, Israel. : ,

TOTAL: **1**

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received	Paper

TOTAL:

Number of Manuscripts:

Books

Received	Book

TOTAL:

Received	Book Chapter
03/14/2017 15.00	Peter L. Read, Boris Galperin, Søren E. Larsen, Stephen R. Lewis, Anni Määttänen, Arakel Petrosyan, Nilton Renno, Hannu Savijärvi, Tero Siili, Aymeric Spiga, Anthony Toigo, Luis Vázquez. The Martian planetary boundary layer, New York - Cambridge: Cambridge University Press, (2017)

TOTAL: **1**

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Esa-Matti Tastula	1.00	
FTE Equivalent:	**1.00**	
Total Number:	**1**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Boris Galperin	0.30	
FTE Equivalent:	**0.30**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ......

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:......

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:......

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):......

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:......

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ......

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: ......

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME
Esa-Matti Tastula
Total Number: **1**

Names of other research staff

NAME	PERCENT_SUPPORTED

FTE Equivalent:
Total Number:

Sub Contractors (DD882)

1 a. Ben-Gurion University of Negev

1 b. Dalet Mizrah

Beersheba, Southern D 00 84105

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

1 a. Numtech

1 b. 6, Allée Alan Turing,

63170 Aubière 00 63170

Sub Contractor Numbers (c):
Patent Clause Number (d-1):
Patent Date (d-2):
Work Description (e):
Sub Contract Award Date (f-1):
Sub Contract Est Completion Date(f-2):

Inventions (DD882)

Scientific Progress

Technology Transfer

The QNSE-based turbulence model has been implemented in WRF model at NCAR

Scientific Progress and Accomplishments

Scientific progress and accomplishments (Description should include significant theoretical or experimental advances) Plain Text Only - If you have diagrams, formula's, etc. in a Word, PDF or other document, enter "See Attachment" below and use the "Attachment" section at the bottom of the menu. This section can include, but is not limited to: (1) Foreword (optional) (2) Table of Contents (if report is more than 10 pages) (3) List of Appendixes, Illustrations and Tables (if applicable) (4) Statement of the problem studied (5) Summary of the most important results (6) Bibliography (7) Appendixes

Foreword

The project was focused on further development, improvement and testing of the QNSE (quasi-normal scale elimination) theory of turbulence on small and large scales and we indeed have made a significant progress in these areas. The major results of this project are enumerated below in a logical rather than the chronological sequence.

List of the Appendixes

Appendix 1 – Formulation of the Deacon numbers

Appendix 2 – Kinetic energy spectra in Jupiter's atmosphere as derived from the Cassini data

Appendix 3 - The Nastrom & Gage spectra

Statement of the problems studied

We further developed the QNSE theory for stably stratified flows, tested it in WRF, expanded the model and paired it with the EDMF (eddy diffusivity – mass flux) approach so that the model could be used in flows with both stable and unstable stratification as required in NWP (numerical weather prediction). Along the way, it became clear that the consistency between an ABL (atmospheric boundary layer) model and near-surface parameterization is critical, and we demonstrated this using the tests based upon the Deacon numbers. One of the important characteristics of stably stratified flows is turbulence anisotropization that can be studied analytically within QNSE and so, we have developed an analytical theory of transition from Kolmogorov to stably stratified turbulence (Sukoriansky & Galperin, 2012). In parallel, we analyzed large-scale flows where turbulence anisotropization is caused by a beta-effect. We found and explored many analogies between these and stably stratified flows. There are, of course, major differences as well, one of the most significant of which is the presence of the downscale energy cascade in stratified flows and upscale cascade in rotating flows with a beta-effect. The differences have also been studies and explored.

Summary of the most important results

1. Reviewing the progress in understanding of stably stratified turbulence and turbulence with a β-effect as of 2010.

The reviews were based upon two invited presentations given at the Workshop on Modeling the Ocean: Dynamics, Syntheses & Predictions, in Taipei, Taiwan, on February 23-26, 2009, and published in *Ocean Dynamics*, see Galperin & Sukoriansky (2010) and Galperin et al. (2010).

We reported on progress in understanding stably-stratified turbulence based upon the quasi-normal scale elimination (QNSE) theory developed by our team in the course of preceding ARO-funded projects (e.g. Sukoriansky et al., 2005; Dr. Sukoriansky from the Ben-Gurion University of the Negev, Israel was a subcontractor for this grant). The theory utilizes successive ensemble averaging of the velocity and temperature modes over the smallest resolved scales of motion and produces corresponding scale-dependent expressions for the eddy viscosity and eddy diffusivity. By extending the process of successive ensemble averaging to the turbulence macroscale, one eliminates all fluctuating scales and arrives at models analogous to the conventional Reynolds stress closures. The scale dependency embedded in the QNSE method reflects contributions from different processes on different scales. Two of the most important processes in stably stratified turbulence, internal wave propagation and flow anisotropization, are explicitly accounted for in the QNSE formalism. For relatively weak stratification, the theory becomes amenable to analytical processing revealing just how increasing stratification modifies the flow field via growing anisotropy and gravity wave radiation. A detailed analytical derivation of the crossover between the Kolmogorov and stably stratified turbulence was given in a later paper by Sukoriansky & Galperin (2013).

The QNSE theory yields the dispersion relation for internal waves in the presence of turbulence and provides a solid theoretical background for the Gargett et al. (1981) scaling of the vertical shear spectrum.

QNSE shows that the internal wave breaking and flow anisotropization void the notion of the critical Richardson number at which turbulence is fully suppressed and flow becomes laminarized. Most of the models being developed today do not involve the critical Richardson number.

QNSE-based formulations for the isopycnal and diapycnal viscosities and diffusivities can be expressed in the form of the Richardson diffusion laws thus providing a theoretical framework for the Okubo dispersion diagrams. Transitions in the spectral slopes are associated with turbulence- and wave-dominated ranges and have direct implications for the transport processes. We show that only quasi-isotropic, turbulence-dominated scales contribute to the diapycnal diffusivity. On larger, buoyancy dominated scales, the diapycnal diffusivity becomes scale-independent. This result underscores the well-known fact that waves can only transfer momentum but not a scalar and sheds a new light upon the Ellison–Britter–Osborn mixing model. QNSE also provides a general framework for separation of the effects of turbulence and waves even if they act on the same spatial and temporal scales. QNSE-based turbulence models have been tested in various applications including the Weather Research and Forecasting (WRF) model and demonstrated reliable performance. These models present viable alternatives to conventional Reynolds stress closures.

Regarding rotating flows with a β-effect, they were considered in the framework of geostrophic turbulence which is a key paradigm in the current understanding of the large-scale planetary circulations. It implies that a flow is turbulent, rotating, stably stratified, and in near-geostrophic balance. When a small-scale forcing is present, geostrophic turbulence features an inverse energy cascade. When the meridional variation of the Coriolis parameter (or a β-effect) is included, the horizontal flow symmetry breaks down giving rise to the emergence of jet flows. The presence of a large-scale drag ensures that the flow attains a steady state. Dependent on the governing parameters, four steady-state flow regimes are possible, two of which are the most practically important. In one of these regimes, a flow is dominated by the drag while in the other, the recently discovered by our group regime of zonostrophic turbulence, a flow becomes strongly anisotropic and features slowly evolving systems of alternating zonal jets. Zonostrophic turbulence is distinguished by anisotropic inverse energy cascade and emergence of a new class of nonlinear waves known as zonons. In addition, meridional scalar diffusion is strongly modified in this regime.

2. The importance of the surface layer parameterization (Tastula et al., 2015b).

The accuracy of prediction of stable atmospheric boundary layers depends on the quality of parameterization of the surface layer which is usually derived using the Monin–Obukhov similarity theory. Stability functions, ϕ_m and ϕ_h, used for the surface layer must be consistent with those used in the bulk of the boundary layer. But how to achieve this consistency? Very often, stability functions in the surface later are taken from interpolating empirical data while in the bulk of ABL, the functions are derived from theoretical models. Assuming that the functions are exactly the same near the ABL surface and in its bulk, QNSE-derived stability functions were compared with several empirical models using the velocity and potential temperature Deacon numbers, D_m and D_h, as the measure of the performance, see Appendix 1. QNSE-derived and other formulations of the Deacon numbers in terms of stability functions were compared with observations from CASES99, Cardington, and Halley datasets. The comparisons were hindered by scatter produced by computing second derivatives from data but general tendencies could be established nevertheless. Tests utilizing $R2$ demonstrated that the QNSE theory exhibits the best overall performance. Further proof of this conclusion was provided by 1D simulations with the WRF model.

3. Methodical assessment of the differences between the QNSE and MYJ PBL schemes for stable conditions (Tastula et al., 2015)

In recent years, the constantly growing number of physics parametrization schemes adopted in numerical weather prediction (NWP) models have resulted in a proliferation of comparative studies. Many of these studies concentrated on determining which parametrization yields results closest to observations rather than analyzing the reasons underlying the differences. This study compared the performance of two 1.5-order boundary layer parameterizations, QNSE and Mellor–Yamada–Janjic (MYJ) schemes, as implemented in WRF. The objectives were to isolate the effect of stability functions on the near-surface values and vertical profiles of virtual temperature, mixing ratio, and wind speed. The results demonstrate that the QNSE stability functions yield better error statistics for 2 m virtual temperature but at higher altitudes the errors related to QNSE are slightly larger for virtual temperature and mixing ratio. A surprising finding is the sensitivity of the model results to the choice of the turbulent Prandtl number for neutral stratification (Pr_{t0}): in the Monin–Obukhov similarity function for heat, the choice of Pr_{t0} is sometimes more important than the functional form of the similarity function itself. There is a stability-related dependence to this sensitivity: with increasing near-surface stability, the relative importance of the functional form increases. In near-neutral conditions, QNSE exhibits too strong vertical mixing attributed to the applied turbulent kinetic energy subroutine and the stability functions, including the effect of Pr_{t0}.

4. The impact of the QNSE-EDMF scheme and its modifications on boundary layer parameterization in WRF: modelling of CASES-97 (Tastula et al., 2015a)

QNSE deals with stably stratified and weakly unstable flows but needs of NWP encompass situations when unstable stratification is strong as well as daily transitions between stable and unstable stratification. Therefore, to be used in NWP, QNSE needs to be supplemented by a scheme capable of dealing with unstable stratification. In recent years, many eddy-diffusivity mass-flux (EDMF) ABL parametrizations have been introduced for this purpose. An EDMF scheme developed by Pergaud et al. (2009) was adopted for our studies, and to implement it in WRF, Julien Pergaud was hired via a subcontract with NumTech, France, where he was employed at that time. Combining QNSE and EDMF and validating this hybrid model in WRF was one of the subjects of the PhD dissertation by Esa-Matti Tastula (he defended his dissertation in 2015). Keeping in mind that most model validations have been based on idealized set-ups and/or single-column models, Esa-Matti addressed this gap in his research by focusing it on the effect of the mass-flux part on the performance of the QNSE-EDMF ABL scheme in WRF. This was achieved by comparing model results to observations from the CASES-97 field campaign. In addition, two refined versions, one introducing the parametrized clouds to the WRF radiation scheme, and the second adding a different entrainment formulation, have been evaluated. The introduction of mass flux reduced errors in the average moisture profile, but virtual temperature and wind speed profiles did not change as much. The modelled mixed-layer depth, while still low compared to observations, was closer to observed values with the addition of the mass flux. The major changes in the virtual potential temperature flux profiles were an increase in entrainment ratios and a slight decrease in surface values. Adding mass-flux-based clouds to the radiation calculation improved the time-and space-averaged modelled incoming short-wave flux.

5. Reviews of the PBL on Mars and turbulence-wave interactions in stably stratified turbulence

The PI of this project, Dr Boris Galperin, was a member of two international working groups that dealt with the Martian PBL and turbulence-wave interaction in stably stratified turbulence. Their activities resulted in two comprehensive reviews published in the Reviews of Geophysics, see Petrosyan et al. (2011) and Sun et al. (2015), to which the PI made major contributions.

6. Zonostrophic turbulence

For many years, we have been studying large-scale turbulence and its anisotropization caused by rotation and a β-effect. We have discovered a new flow regime of anisotropic turbulence which we coined *zonostrophic turbulence* (e.g. Galperin et al., 2010). Over a short time, this term has become widely used in geophysical fluid dynamics and even applied to non-turbulent phenomena. But due to the lack of data, it was impossible to validate our prediction going back to the papers by Huang et al. (2001) and Galperin et al. (2001) that the regime of zonostrophic turbulence is characteristic of the Jupiter atmosphere. The data was only sufficient to confirm that the zonal spectrum, $E_Z(n)$, is congruent to this regime, $E_Z(n) = C_Z (\Omega/R)^2 n^{-5}$, where C_Z is an O(1) constant, Ω and R are planetary angular velocity and radius, and n is the total planetary wavenumber (Galperin et al., 2001), but not the residual one which was predicted to preserve its Kolmogorov form, $E_R(n) = C_K \varepsilon^{2/3} n^{-5/3}$, where $C_K \approx 6$ is the Kolmogorov constant. After NASA made public the Cassini data collected during the Jupiter flyby in 2000, it became possible to validate our prediction for the residual spectrum as well and it was done in Galperin et al. (2014b). Three daily-averaged two-dimensional velocity snapshots extracted from Jupiter images were used to perform spectral analysis of Jovian atmospheric macroturbulence. The analysis revealed strong anisotropy of the kinetic energy spectrum shown in Appendix 2. The zonal spectrum was very steep and most of the kinetic energy resided in slowly evolving, alternating zonal (west–east) jets, while the non-zonal, or residual spectrum obeyed the Kolmogorov–Kraichnan law specific to two-dimensional turbulence in the range of the inverse energy cascade. The spectral data was used to estimate the inverse cascade rate ε and the zonostrophy index R_β for the first time. The estimate of ε was in the range 0.5–1.0 x 10^{-5} m^2 s^{-3}. The ensuing values of $R_\beta >= 5$, well in the range of zonostrophic turbulence whose threshold corresponds to $R_\beta \sim 2.5$.

It was inferred that the large-scale circulation is maintained by an anisotropic inverse energy cascade. The removal of the Great Red Spot had no significant effect upon the spectra or the inverse cascade rate. The spectral data was used to compute the rate of the energy exchange, W, between the non-zonal structures and the large-scale zonal flow. It was found that instantaneous values of W may exceed ε by an order of magnitude. Previous numerical simulations with a barotropic model suggest that W and ε attain comparable values only after averaging of W over a sufficiently long time. Near-instantaneous values of W that have been routinely used to infer the rate of the kinetic energy supply to Jupiter's zonal flow may therefore significantly overestimate ε. The disparity between W and ε may resolve the long-standing conundrum (the so-called Suomi paradox) of an unrealistically high rate of energy transfer to the zonal flow. The meridional diffusivity K_y in the regime of zonostrophic turbulence is given by an expression that depends on ε. The value of K_y estimated from the spectra was compared against data from the dispersion of stratospheric gases and debris resulting from the Shoemaker-Levy 9 comet and Wesley asteroid impacts in 1994 and 2009 respectively. Not only is K_y was found to be consistent with estimates for both impacts, but the eddy diffusivity found from observations appeared to be scale-independent. This behavior could be a consequence of the interaction between anisotropic turbulence and Rossby waves specific to the regime of zonostrophic macroturbulence.

7. Experimental research – potential vorticity monotonizing

In parallel with the theoretical, numerical and observational research on anisotropic turbulence encompassing virtually all scales, PI also engaged in the collaborative experimental research with colleagues who run a facility (rotating table) at the University of Rome (Galperin et al., 2014a, 2016). A westward propagating jet was investigated in this facility. The focus was on complex interaction between anisotropic turbulence with inverse energy cascade and Rossby waves. The energy spectrum was highly anisotropic. To diagnose turbulence characteristics, an analogy between turbulent overturns in stably stratified and quasi-geostrophic flows was explored and a novel method based upon the monotonizing of potential vorticity (PV) was developed. The RMS displacement from the monotonic PV profile yields a length scale, L_M, analogous to the Thorpe's scale used in flows with stable stratification. As the Thorpe scale is proportional to the Ozmidov scale, the scale L_M turned out to be proportional to the scale $L_\beta=(\varepsilon/\beta^3)^{1/5}$, ε being the rate of the inverse energy cascade, at which the time scales of turbulent overturns and Rossby waves are approximately equal. The relationship between L_M and L_β, $L_M/L_\beta \approx 4$, was established for the first time. The method of PV monotonizing offers a simple and powerful tool for diagnosing geophysical and planetary macroturbulence, the same way as the Thorpe scale offers a simple and powerful tool to diagnose vertical mixing in the oceans and the atmospheres. The experimental research was extended further, to analyze lateral diffusion in fluids with zonal jets (Galperin et al., 2016).

8. Turbulence anisotropisation and Nastrom & Gage spectra in rotating flows

Under the action of solid body rotation, homogeneous neutrally stratified turbulence undergoes anisotropisation and onset of the inverse energy cascade. These processes were investigated using the QNSE theory (Sukoriansky & Galperin, 2016). The effect of rotation increases with increasing scale and manifests in anisotropisation of the eddy viscosities, eddy diffusivities, and kinetic energy spectra. Not only the vertical and horizontal eddy viscosities and eddy diffusivities become different but, reflecting both directional and componental anisotropisation, there emerge four different eddy viscosities. Three of them decrease relative to the eddy viscosity in non-rotating flows while one increases. This behavior is indicative of increasing redirection of the energy flux to larger scales. On scales comparable to the Woods scale, $L_\Omega = [\varepsilon/(2\Omega)^3)]^{1/2}$, ε being the rate of the viscous dissipation and Ω is the rate of the angular velocity of system rotation (by construction, L_Ω is the rotational analogue of the Ozmidov length scale in stably stratified flows), the horizontal viscosity rapidly decreases, and in order to keep it positive, a weak rotation limit is invoked. Within that limit, an analytical theory of the transition from the Kolmogorov to a rotation-dominated turbulence regime is developed. The dispersion relation of linear inertial waves is unaffected by turbulence while all one-dimensional energy spectra undergo steepening from the Kolmogorov -5/3 to the -3 slope. The theoretical expressions for the horizontal kinetic energy spectra recover the famous observations of the atmospheric spectra by Nastrom & Gage as shown in Appendix 3. The theoretical spectra are in a remarkable agreement with observational and numerical data. The theory explains the latitudinal dependence of the Nastrom & Gage spectra and confirms that the energy flux is downscale throughout all scales. QNSE theory explains the physical nature of the Nastrom & Gage spectra for the first time and provides a unique tool for validation of numerical models.

Bibliography

Choi, D. & A. Showman, 2011: Power spectral analysis of Jupiter's clouds and kinetic energy from Cassini. *Icarus*, **216**, 597–609.

Galperin, B., J. Hoemann, S. Espa & G. Di Nitto, 2014a: Anisotropic turbulence and Rossby waves in an easterly jet: An experimental study. *Geophysical Research Letters*, **41**, 6237–6243. doi:10.1002/2014GL060767.

Galperin, B., J. Hoemann, S. Espa, G. DiNitto & G. Lacorata, 2016: Anisotropic macroturbulence and diffusion associated with a westward zonal jet: From laboratory to planetary atmospheres and oceans. Physical Review E, **94**, 063102. doi: 10.1103/PhysRevE.94.063102.

Galperin, B. & S. Sukoriansky, 2010: Geophysical flows with anisotropic turbulence and dispersive waves: flows with stable stratification. *Ocean Dynamics,* **60**, 1319–1337, doi: 10.1007/s10236-010-0325-z.

Galperin, B., S. Sukoriansky & N. Dikovskaya, 2010: Geophysical flows with anisotropic turbulence and dispersive waves: flows with a β-effect. *Ocean Dynamics*, **60,** 427–441, doi:10.1007/s10236-010-0278-2.

Galperin, B., S. Sukoriansky & H.-P. Huang, 2001: Universal n^{-5} spectrum of zonal flows on giant planets. *Physics of Fluids*, **13**, 1545-1548.

Galperin, B., S. Sukoriansky, N. Dikovskaya, R.M.B. Young, P.L. Read, A.J. Lancaster & D. Armstrong, 2014b: Cassini observations reveal a regime of zonostrophic macroturbulence on Jupiter. *Icarus*, **229**, 295-320. doi:10.1016/j.icarus.2013.08.030.

Gargett, A., P. Hendricks, T. Sanford, T. Osborn & A. Williams III, 1981 A composite spectrum of vertical shear in the upper ocean. *Journal of Physical Oceanogrophy*, **11**, 1258–1271. (doi:10.1175/1520-0485(1981)011<1258:ACSOVS>2.0.CO;2)

Huang, H., B. Galperin & S. Sukoriansky, 2001: Anisotropic spectra in two-dimensional turbulence on the surface of a rotating sphere. *Physics of Fluids*, **13**, 225-240.

Pergaud, J., V. Masson, S. Malardel & F. Couvreux, 2009: A parameterization of dry thermal and shallow cumuli for mesoscale numerical weather prediction. *Boundary-Layer Meteorol.,* **132,** 83–106.

Petrosyan, A., B. Galperin, S.E. Larsen, S.R. Lewis, A. Määttänen, P.L. Read, N. Renno, L.P.H.T. Rogberg, H. Savijarvi, T. Siili, A. Spiga, A. Toigo & L. Vazquez, 2011: The Martian atmospheric boundary layer. *Reviews of Geophysics*, **49,** RG3005, doi: 10.1029/2010RG000351.

Sun, J., C.J. Nappo, L. Mahrt, D. Belušic, B. Grisogono, D.R. Stauffer, M. Pulido, C. Staquet, Q. Jiang, A. Pouquet, C. Yagüe, B. Galperin, R.B. Smith, J.J. Finnigan, S.D. Mayor, G. Svensson, A.A. Grachev & W.D. Neff, 2015: Review of wave-turbulence interactions in the stable atmospheric boundary layer. *Rev. Geophys*., **53**, 956–993, doi:10.1002/2015RG000487.

Sukoriansky, S., N. Dikovskaya, R. Grimshaw & B. Galperin, 2012: Rossby waves and zonons in zonostrophic turbulence. AIP Conf. Proc. **1439**, 111-122; doi: 10.1063/1.3701355.

Sukoriansky, S. & B. Galperin, 2013: An analytical theory of the buoyancy - Kolmogorov subrange transition in turbulent flows with stable stratification. *Philosophical Transactions of the Royal Society*, *Series* A – Mathematics, Physics, Engineering Science, **371,** SI, UNSP 20120212, doi: 10.1098/rsta.2012.0212 Published: JAN 13 2013.

Sukoriansky, S., & B. Galperin, 2016: QNSE theory of turbulence anisotropization and onset of the inverse energy cascade by solid body rotation. *Journal of Fluid Mechanics*, **805,** 384-421, doi:10.1017/jfm.2016.568.

Tastula, E.-M., B. Galperin, J. Dudhia, M.A. LeMone, S. Sukoriansky & T. Vihma, 2015a: Methodical assessment of the differences between the QNSE and MYJ PBL schemes for stable conditions. *Quarterly Journal of the Royal Meteorological Society*, **141**, 2077–2089, DOI:10.1002/qj.2503.

Tastula, E.-M., B. Galperin, S. Sukoriansky, A. Luhar & P. Anderson, 2015b: The importance of surface layer parameterization in modeling of stable atmospheric boundary layers. *Atmospheric Science Letters*, **16**, 83-88, doi:10.1002/asl2.525.

Tastula, E.-M., M.A. LeMone, J. Dudhia & B. Galperin, 2016: The impact of the QNSE-EDMF scheme and its modifications on boundary layer parameterization in WRF: modeling of CASES-97. *Quarterly Journal of the Royal Meteorological Society*, **142**, 1182–1195. doi:10.1002/qj.2723

Tastula, E.-M., T. Vihma, E. Andreas & B. Galperin, 2013: Validation of the diurnal cycles in atmospheric reanalyses over Antarctic sea ice. *Journal of Geophysical Research - Atmospheres*, **118**, 4194-4204. doi:10.1002/jgrd.50336.

Appendix 1.

Formulation of the Deacon numbers

The Deacon numbers are defined based upon the profiles of mean velocity and mean potential temperature, U and Θ, as well as the corresponding stability functions, ϕ_m and ϕ_h,

$$D_m \equiv -z\frac{d^2U}{dz^2}/\frac{dU}{dz} = 1 - \frac{\zeta}{\phi_m(\zeta)}\frac{d\phi_m(\zeta)}{d\zeta} = 1 - \frac{d\ln\phi_m(\zeta)}{d\ln\zeta},$$

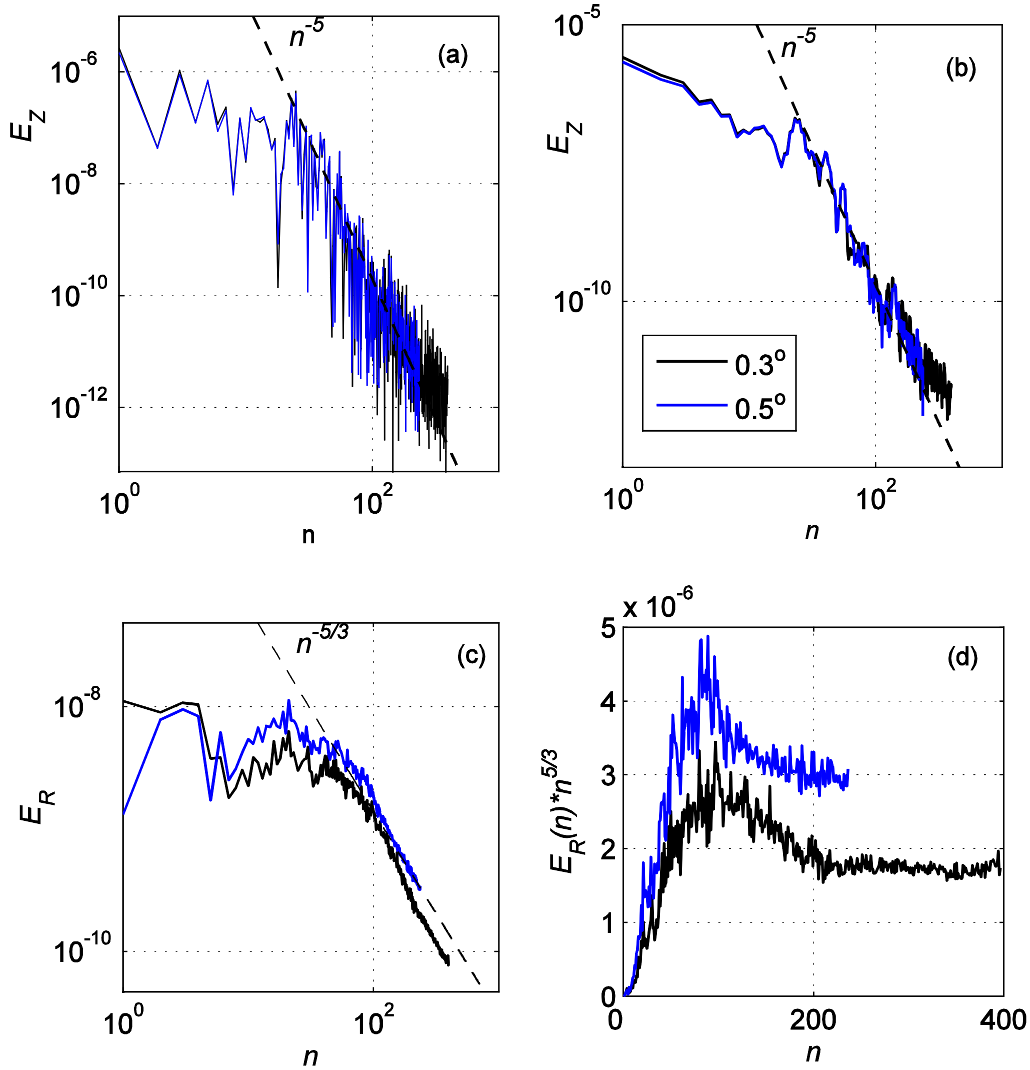
$$D_h \equiv -z\frac{d^2\Theta}{dz^2}/\frac{d\Theta}{dz} = 1 - \frac{\zeta}{\phi_h(\zeta)}\frac{d\phi_h(\zeta)}{d\zeta} = 1 - \frac{d\ln\phi_h(\zeta)}{d\ln\zeta},$$

where $\zeta = z/L$, L being the Monin-Obukhov length scale. Instead of ζ, one can use the gradient Richardson number,

$$Ri_g \equiv \frac{g}{\Theta_0}\frac{d\Theta}{dz}\left(\frac{dU}{dz}\right)^{-2} = \frac{\zeta\phi_h(\zeta)}{\phi_m^2(\zeta)}.$$

Appendix 2.

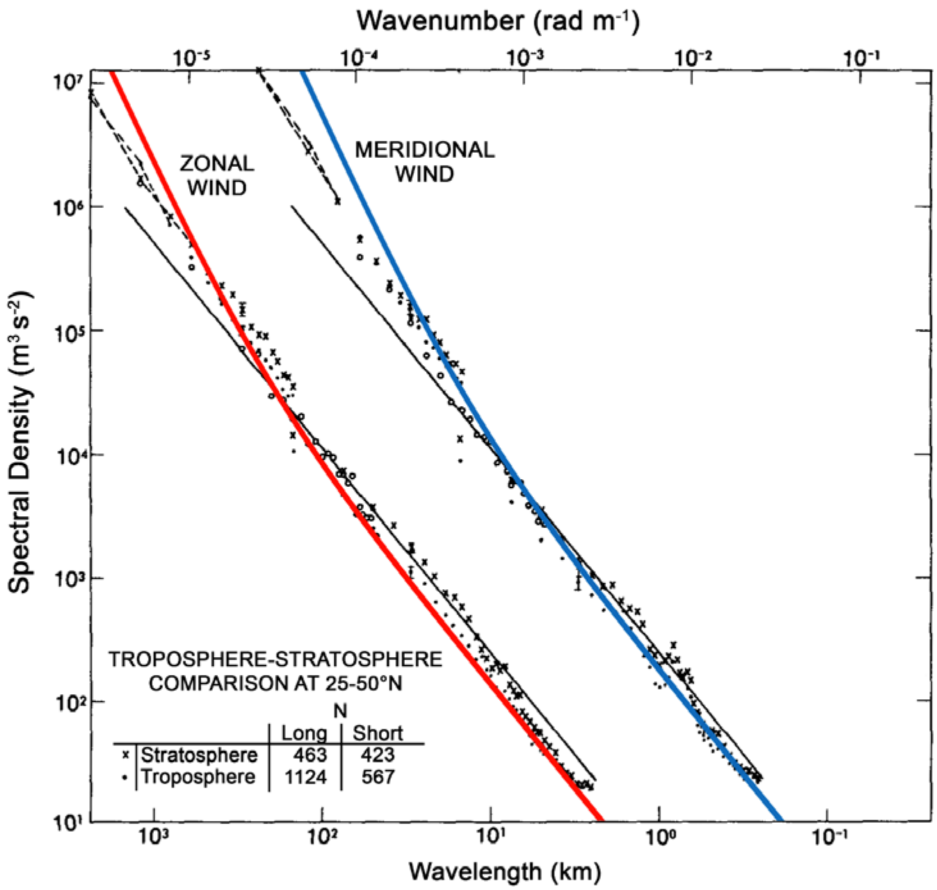
Kinetic energy spectra in Jupiter's atmosphere as derived from the Cassini data.



Zonal and residual kinetic energy spectra on Jupiter computed from Galperin et al. (2014b) data with grid spacing of 0.5° (blue) and from the Choi & Showman (2011) data with grid spacing of 0.3° (black). (a): Three-day averaged zonal spectra $E_Z(n)$; the dashed line corresponds to the equation given earlier with C_Z=2. (b): spectra from (a) smoothed using a moving box algorithm with a five point stencil. (c): same as (a) but for the residual spectra $E_R(n)$; the dashed line corresponds to the Kolmogorov spectrum above. (d): Compensated residual spectra $C_R=E_R(n)\ n^{5/3}$ derived from (c).

Appendix 3.

The Nastrom & Gage spectra



Comparison of the kinetic energy spectra in the troposphere and stratosphere in the latitudinal band 25° N - 50° N with the theoretical QNSE predictions shown by the red and blue lines. Straight black lines show Kolmogorov's -5/3 slope.