

# MEETING SUMMARIES

## NORMAL MODES OF ATMOSPHERIC VARIABILITY IN OBSERVATIONS, NUMERICAL WEATHER PREDICTION, AND CLIMATE MODELS

BY NEDJELJKA ŽAGAR, JOHN BOYD, AKIRA KASAHARA, JOSEPH TRIBBIA, ERLAND KÄLLÉN, HIROSHI TANAKA, AND JUN-ICHI YANO

**MOTIVATION.** Normal modes, which we deal with here, are eigensolutions to the linearized primitive equations of the atmosphere. Known as the solutions of the first and second kinds or inertia–gravity (IG) and balanced (Rossby type) oscillations, normal modes have been extensively applied for the initialization of numerical weather prediction (NWP) models in the 1980s to early 1990s. The global horizontal structures of normal modes, known as Hough functions, have been used to study various

**AFFILIATIONS:** ŽAGAR—University of Ljubljana, Ljubljana, Slovenia; BOYD—University of Michigan, Ann Arbor, Michigan; KASAHARA and TRIBBIA—National Center for Atmospheric Research,\* Boulder, Colorado; KÄLLÉN—European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom; TANAKA—University of Tsukuba, Tsukuba, Ibaraki, Japan; YANO—CNRM-GAME, Météo-France, and CNRS, Toulouse, France  
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**CORRESPONDING AUTHOR:** Nedjeljka Žagar, University of Ljubljana, Faculty of mathematics and Physics, Jadranska 19, 1000 Ljubljana, Slovenia  
E-mail: nedjeljka.zagar@mf.uni-lj.si

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### MODES WORKSHOP

**WHAT:** Around 40 scientists from five continents discussed the applications of normal-mode functions (NMFs) in atmospheric research and operations. The application areas include data assimilation and initialization of numerical weather prediction (NWP) models, the use of NMFs as building blocks of simplified models of tropical circulation, and the identification of the 2D and 3D structure of normal modes in observations, reanalyses, and NWP and climate models.

**WHEN:** 26–29 August 2015

**WHERE:** National Center for Atmospheric Research, Boulder, Colorado

atmospheric dynamical phenomena in weather and climate. The basic properties of the large-scale circulations in the tropics for both the atmosphere and oceans have been elucidated in terms of normal modes on the equatorial beta plane.

In the last decade, global data assimilation and forecasting systems have reached resolutions at which IG waves across many scales have become resolved. Furthermore, a rich spectrum of the equatorially trapped IG and the mixed Rossby–gravity waves, in addition to the equatorial Kelvin and Rossby waves, has been identified in observations.

At the same time, significant uncertainties in the initial state for NWP models still exist in the tropics, and they are in part associated with the representation of IG waves on many scales. Clearly, the initialization of the unbalanced component of global circulation is a difficult problem in the situation when the role of IG waves with respect to the balanced circulation on various scales is rather uncertain. Furthermore, the observational studies are based almost exclusively on temperature observations that are abundant in contrast to the wind measurements, especially in the tropics. The three-dimensional (3D) picture of the atmospheric, unbalanced circulation thus relies on analysis data, including uncertainties associated with the lack of direct wind observations and with deficiencies of the applied NWP models and data assimilation procedures.

In the midlatitudes, divergence has been used as a proxy for inertia–gravity waves, especially on the mesoscale. In the tropics, the IG waves span the whole spectrum and some are characterized by a significant portion of vorticity. For example, the Kelvin mode, the most energetic gravity oscillation of the global atmosphere, is characterized by an equipartition between vorticity and divergence.

For global datasets, the IG waves can be obtained by projecting 3D wind and mass data to the normal modes of the global, linearized equations. The pioneering work of National Center for Atmospheric Research (NCAR) scientists provides solutions for the three-dimensionally orthogonal normal-mode functions (NMFs) of the primitive equations on terrain-following levels in terms of the discrete spectrum of the Rossby and inertia–gravity waves and their zonally averaged states. Based on this set of normal modes, a representation of the IG and balanced modes of the global atmosphere by the European Centre for Medium-Range Weather Forecasts (ECMWF) deterministic model has recently become available in real time (<http://meteo.fmf.uni-lj.si/MODES>). The related MODES workshop revisited the three application areas of NMFs pointed out by Dickinson and Williamson (1972): the initialization of NWP models, the identification of model modes that have significance for climate simulations, and the comparison of amplitudes of model modes with those observed in the real atmosphere. While the initialization of NWP models by using the normal modes was explored a few decades ago, the other two application areas have received little attention. The workshop thus focused on the diagnostic aspect of NMF

applications. Normal modes are resonant states of the global atmospheric circulation, and it is of interest to understand how much of the circulation energetics can be attributed to them as the circulation regimes associated with resonant modes are intrinsically more predictable than fully nonlinear, turbulent structures.

#### *Normal-mode functions and NWP balancing issues.*

The NMFs have been in use since the late 1970s for the nonlinear normal-mode initialization (NNMI) of NWP models. However, the NNMI did not require 3D orthogonality, and thus the applied vertical and horizontal structure functions have only been orthogonal in the phase space of the NWP model. A global NWP system that still applies the NNMI on the analysis increments is the National Centers for Environmental Prediction (NCEP) deterministic and ensemble prediction system. The presented results illustrated the importance of the choice of unbalanced modes and vertical truncation for the balanced initial state, especially in ensemble Kalman filter applications. These issues have been addressed since the 1980s in relation to the interpretation of the vertical structure functions and the relation between the NMFs and singular vectors in quasigeostrophic dynamics. The NMF decomposition has been demonstrated to help in the identification of the NWP initial errors in the tropics and in the identification of modes that are needed in the ensemble prediction system to maintain its spread close to the root-mean-square error. While some midlatitude forecast failures in the medium range can be traced back to the tropical initial state, high-resolution mesoscale models in midlatitudes struggle from the problems experienced at the early stage of global NWP: a relatively quick loss of the impact of analysis increments from mesoscale observations. Like the tropics, the mesoscale balance issues are intimately related to the role of inertia–gravity dynamics.

#### *Identification of normal modes in observations and reanalyses.*

While the earliest evidence of the normal-mode structure in atmospheric observations goes back to the 1950s, a systematic derivation of the frequencies of the leading balanced and IG modes was provided by A. Kasahara at NCAR around 1980. At the workshop, R. Madden showed that Rossby modes with predicted periods are found in the modern reanalysis data (e.g., ECMWF interim reanalyses).

The most involved use of normal modes has been in tropical meteorology. Historically, the Kelvin and Rossby waves with the lowest meridional modes have been extensively utilized in simplified models of

tropical dynamics in both the atmosphere and ocean. In particular, these modes are associated with the stationary response to heating obtained from equations including the long-wave approximation. More recent observations and modeling results reveal an important role played by IG waves in addition to the Kelvin mode. High-resolution satellite datasets [e.g., SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) and HIRDLS (High-Resolution Dynamics Limb Sounder)] provide information on temporal and spatial variability of the equatorial IG waves in the stratosphere and mesosphere that can be used for the verification of NWP models. The most clearly identified mode is the Kelvin wave characterized by geostrophic coupling between the zonal wind and the meridional temperature gradient. Furthermore, the equatorially trapped Rossby and Kelvin modes have been considered the two main ingredients of the Madden–Julian oscillation (MJO), a leading mode of tropical intraseasonal variability. A new conceptual model of MJO presented by J.-I. Yano is based on a strongly nonlinear Rossby mode.

More recently, the identification of equatorial waves in the reanalysis data has been carried out also by the global 3D NMF representation. In comparison to other methods, such as the spectral space–time filtering, the modes diagnosed in terms of 3D orthogonal NMFs can be quantified for their contribution to the global variability. Overall, prominent Rossby and IG modes with periods predicted by the linear theory have been identified in various datasets, and the importance of their validation in climate models was highlighted.

*Formulation of normal modes and atmospheric modes of variability.* The NMF representation is an efficient tool for the representation of the atmospheric energy distribution in the balanced and inertia–gravity regimes. Such a separation is particularly useful on the large scales where the traditionally used spherical harmonics are of little use in physical interpretation. Thanks to their 3D orthogonality, NMFs could be used to estimate the global level of IG wave energy at around 8% based on ERA-Interim reanalyses. This number significantly exceeds the previous estimates based on analysis systems one to two decades old. A comparison showed that more recent datasets with higher horizontal and vertical resolutions reflect advancements in the quality of atmospheric analyses, especially the large-scale tropical flow including the vertically propagating IG waves. The same NMF methodology quantifies components of the Lorenz energy diagram.

There are already extensive theoretical studies on nonlinear aspects of normal modes and, more

specifically, for the Kelvin waves, the most studied mode of tropical variability. Extensive applications of the spherical and nonlinear dynamics aspects of the Kelvin wave are still to be seen. Moreover, global nonhydrostatic normal modes were derived, and their weakly nonlinear aspects were discussed in several studies. Within the revival of the application of the Hough functions, J. Boyd announced a coming book revisiting Longuet-Higgins’ masterwork half a century later.

*The MODES software.* One of the workshop goals was a presentation of the MODES software that allows diagnostics of properties of balanced and inertia–gravity circulation in global 3D datasets. The software is described in Žagar et al. (2015) and is currently available online (<http://meteo.fmf.uni-lj.si/MODES>). It can be used to analyze data in both Grib and NetCDF format from a number of reanalysis datasets and phase 5 of the Coupled Model Intercomparison Project (CMIP5) models.

**SUMMARY.** The workshop has seen extensive presentations on the normal-mode decomposition of data, wave analysis, as well as associated theoretical and observational studies. In particular, a significant contribution of the IG modes in atmospheric variability is established in the NWP models, in reanalysis datasets, and in climate simulations. As the tropics are a problematic area in many climate models, validation of simulated atmospheric variability in terms of NMFs is likely to provide useful information about model deficiencies. However, the role of IG modes in atmospheric circulations is still to be clearly identified: does it demonstrate an importance of linear IG waves in many atmospheric scales or that the IG modes are required in order to maintain a nonlinear balance? The NMFs may be seen as complementary to other orthogonal representations of modes of the atmospheric variability such as empirical orthogonal functions (EOFs). However, the NMF decomposition extracts physical wave modes that constitute solutions to the global linear primitive equation system. This makes the use of NMFs advantageous for diagnostic purposes, for isolating NWP issues, and the potential for improved prediction skill (e.g., the MJO). The use of the NMF decomposition is straightforward once we have the normal-mode solutions in hand. A part of the goal of the aforementioned MODES software was to overcome this last obstacle so that the normal-mode approach can be more extensively and widely exploited in the atmospheric and climate communities. We

see potentials for more objective validations of the climate models under the normal-mode approach.

More information about the meeting can be found on the workshop web page, where a majority of the presented talks have been published (<https://www2.cgd.ucar.edu/sections/amp/events/20150826/presentations-posters>).

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## REFERENCES

- Dickinson, R. E., and D. L. Williamson, 1972: Free oscillations of a discrete stratified fluid with application to numerical weather prediction. *J. Atmos. Sci.*, 29, 623–640, doi:10.1175/1520-0469(1972)029<0623:FOOADS>2.0.CO;2.
- Žagar, N., A. Kasahara, K. Terasaki, J. Tribbia and H. Tanaka, 2015: Normal-mode function representation of global 3-D data sets: open-access software for the atmospheric research community. *Geosci. Model Dev.*, 8, 1169–1195, doi:10.5194/gmd-8-1169-2015.