TEMPEST

Paul Ullrich, University of California, Davis

A comprehensive simulation-to-science infrastructure that tackles the needs of next-generation, high-resolution, data intensive climate modeling activities.

TempestDynamics

With Jorge Guerra[1]
[1] University of California, Davis

Motivation

As atmospheric models are pushed towards finer resolutions, there is a need for accurate and robust numerical methods which are effective for modeling flows on large-scale parallel systems. The next generation of atmospheric general circulation models will also need to support a range of features: They will be expected to solve the non-hydrostatic equations of motion on static and dynamically adaptive meshes and support physics/land/ocean coupling on separate, process-dependent time scales. To better understand which technologies are best suited for the next generation of global models, Tempest seeks to provide a framework for easy intercomparison and testing of these features.

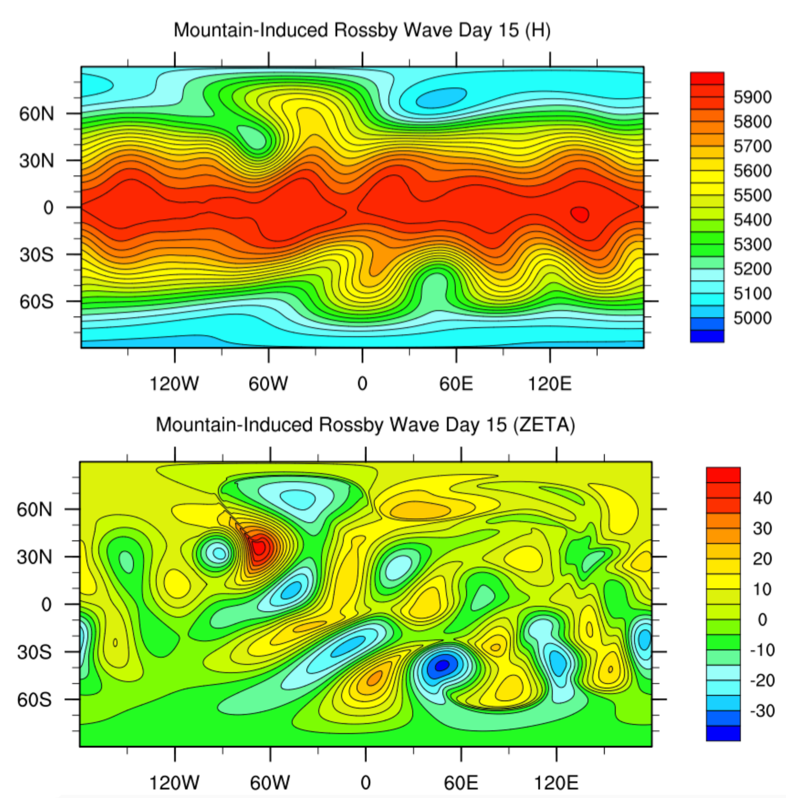


Figure: Simulations of a mountain-induced shallow water Rossby wave train at 28km global resolution.

Mesh and Refinement

Tempest uses non-conformal block-based mesh refinement on the cubed-sphere grid. This approach allows for dynamic adaptation of the mesh to follow features of interest and sub-cycling in time to improve performance (that is, the coarser resolution mesh uses a larger time step than at finer resolutions).

Figure: A non-conformal block-refined mesh with three levels of mesh refinement over California.

Numerical Methods

Tempest provides a framework for several high-order compact numerical methods within a single code base, including spectral element (SE), discontinuous Galerkin (DG), flux reconstruction (FR) and staggered nodal finite-element (SNFEM) methods. These compact methods have been shown (Ullrich, 2013) to have among the best linear wave-capturing properties among all known local numerical discretizations. High-order coupling in time is provided via an implicit-explicit adaptive Runge-Kutta (ARK) method. In this formulation vertically propagating sound waves are captured implicitly and so do not affect model stability.

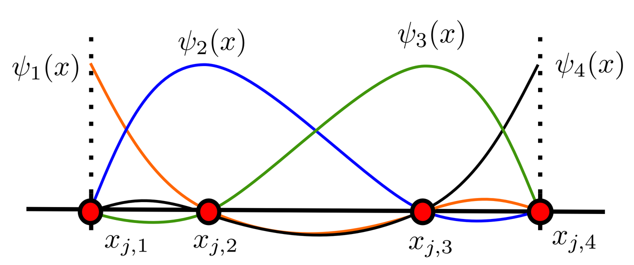


Figure (Above): Gauss-Lobatto-Legendre basis functions for a horizontal spectral element discretization.

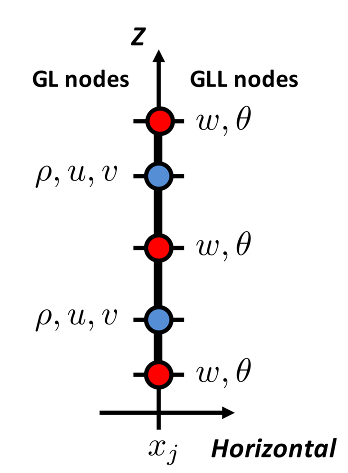
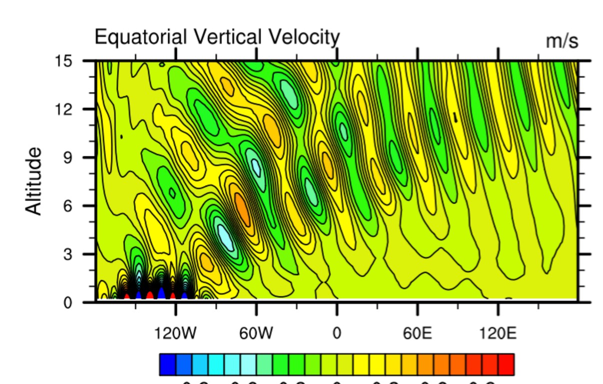


Figure (Above): Following Toy and Randall (2007) and Thuburn (2006) HARDcore uses a (wθ,ρuv) staggering of prognostic variables in the vertical. High-order is achieved via a mixed finite-element approach using both the spectral element and discontinuous Galerkin formulation. Vertical timestepping is via an implicit Jacobian-free formulation.

Figure (Below): Vertical velocity response to a Schär-type Mountain on a small spherical Earth.



Component Architecture

To allow for easy interchange of model components and physical parameterizations, the architecture is formulated using object-oriented C++ at the highest level with interconnections to Fortran for low-level processing. Remeshing is handled in parallel on local processors to avoid overhead due to extraneous communication with the coupler.

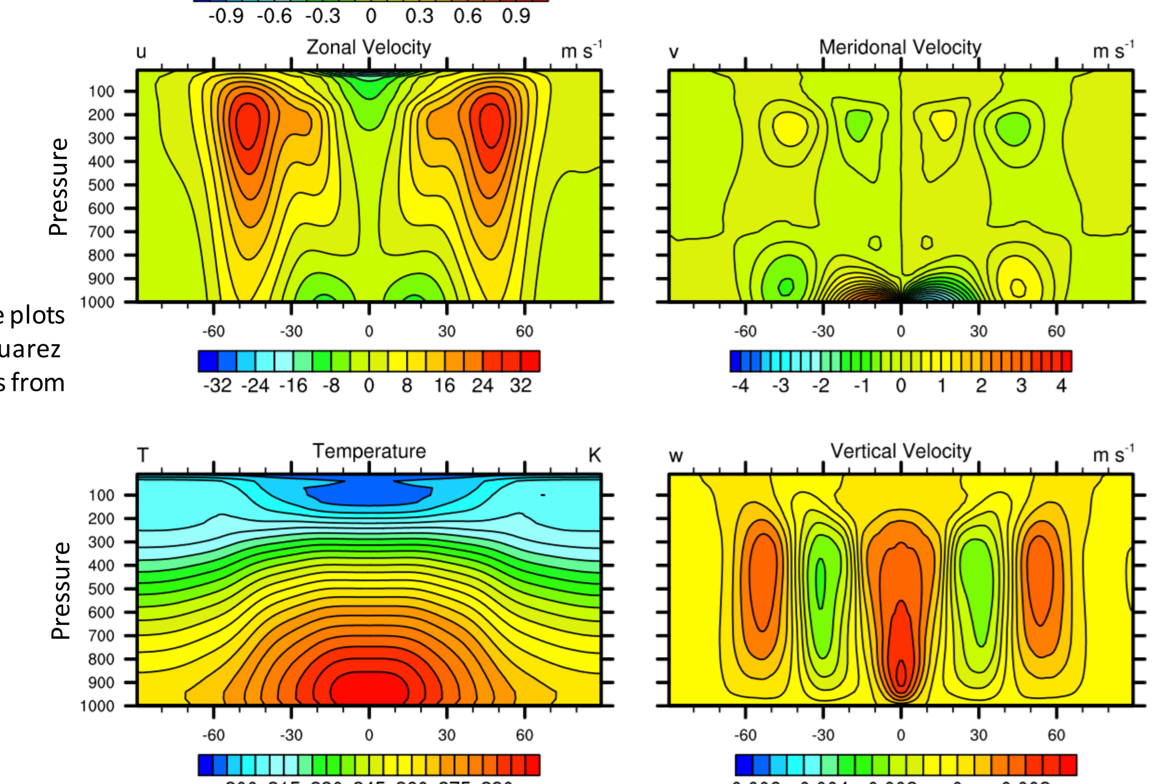


Figure (Right): Latitude-Pressure plots displaying Held-Suarez simulation results from Tempest.

References

- Dennis, JM, et al. (2012) "CAM-SE: A scalable spectral element dynamical core for the Community Atmosphere Model." *Int. J. High Perform. Comput. Appl.* 26 (1): 74-89.
- Huynh, HT (2007) "A flux reconstruction approach to high-order schemes including discontinuous Galerkin methods." *AIAA paper* 4079.
- Thuburn, J (2006) "Vertical discretizations giving optimal representation of normal modes: Sensitivity to the form of the pressure-gradient term." *Quart. J. Royal Meteor. Soc*, 132 (621): 2809-2825.
- Toy, Michael D., and David A. Randall (2007). "Comment on the article "Vertical discretizations for compressible Euler equation atmospheric models giving optimal representation of normal modes" by Thuburn and Woollings." *J. Comput. Phys.* 223 (1): 82-88.
- Ullrich, PA (2014) "Understanding the treatment of waves in atmospheric models, Part I: The shortest resolved waves of the 1D linearized shallow water equations." *Quart. J. Royal Meteor. Soc.,* 140 (682): 1426-1440.
- Ullrich, PA (2014) "A global finite-element shallow-water model supporting continuous and discontinuous elements." *Geosci. Model Dev. Discuss.*, 7: 5141-5182.

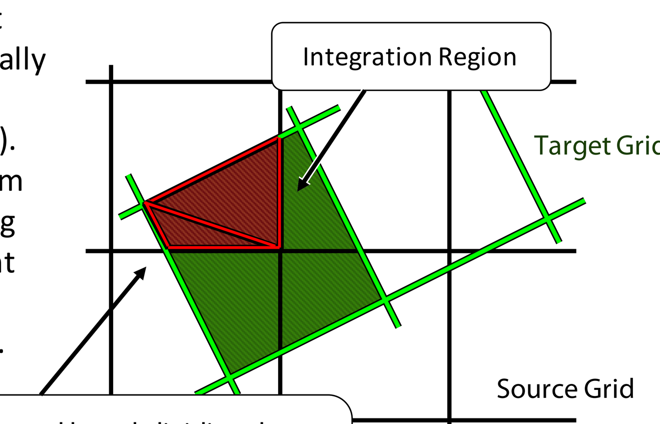
TempestRemap

With Mark Taylor[2], Hans Johansen[3], Dharshi Devendran[3]
[2] Sandia National Laboratories [3] Lawrence Berkeley National Lab

Motivation

The design of accurate, conservative, consistent and monotone operators for remapping scalar fields between computational grids on the sphere has been a persistent issue for global modeling groups. This problem is especially pronounced when mapping between distinct discretizations (such as finite volumes or finite elements). To this end, TempestRemap provides a unified mechanism for conservative, consistent and/or monotone remapping between grids of arbitrary geometry. Both finite element meshes (spectral element, discontinuous Galerkin) and finite volume meshes (element averages) are supported.

Step 1: A "first guess" map is constructed using an understanding of the geometry to preserve locality.



Step 2: The "first guess" map is projected into the space of conservative and consistent maps using least squares.

Integration is performed by subdividing the region into triangles and using **triangular quadrature** over each region.

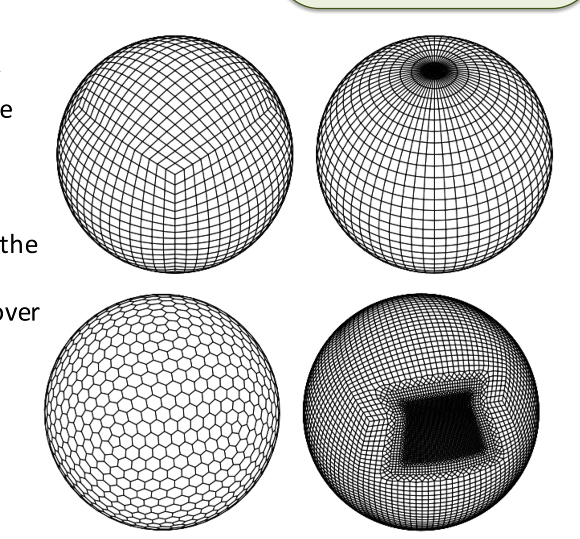
Step 3: The updated map is augmented with a low-order monotone map if needed to preserve monotonicity.

Flexibility and Utility

$$\hat{R}_{ij} = \hat{R}^*_{ij} - \mathbf{C}^T(\mathbf{C}\mathbf{C}^T)^{-1}\left[\mathbf{C}\hat{R}^*_{ij} + \begin{pmatrix} 1 \\ J^s \end{pmatrix}\right]$$

The resulting linear maps are stored in SCRIP (NetCDF) format, and so can be applied via a computationally efficient sparse matrix multiply operation. The maps support arbitrary order-of-accuracy, and can be theoretically shown to exactly preserve conservation and consistency. These maps can also be applied using a non-linear operator to maintain high-order accuracy and monotonicity in the presence of discontinuities in the field.

Figure (Right): Arbitrary unstructured meshes are supported by the remapping software, including meshes with incomplete coverage of the sphere. Finite element meshes are supported over quadrilaterals.



Finite Element Source Grid → Finite Volume Target Grid

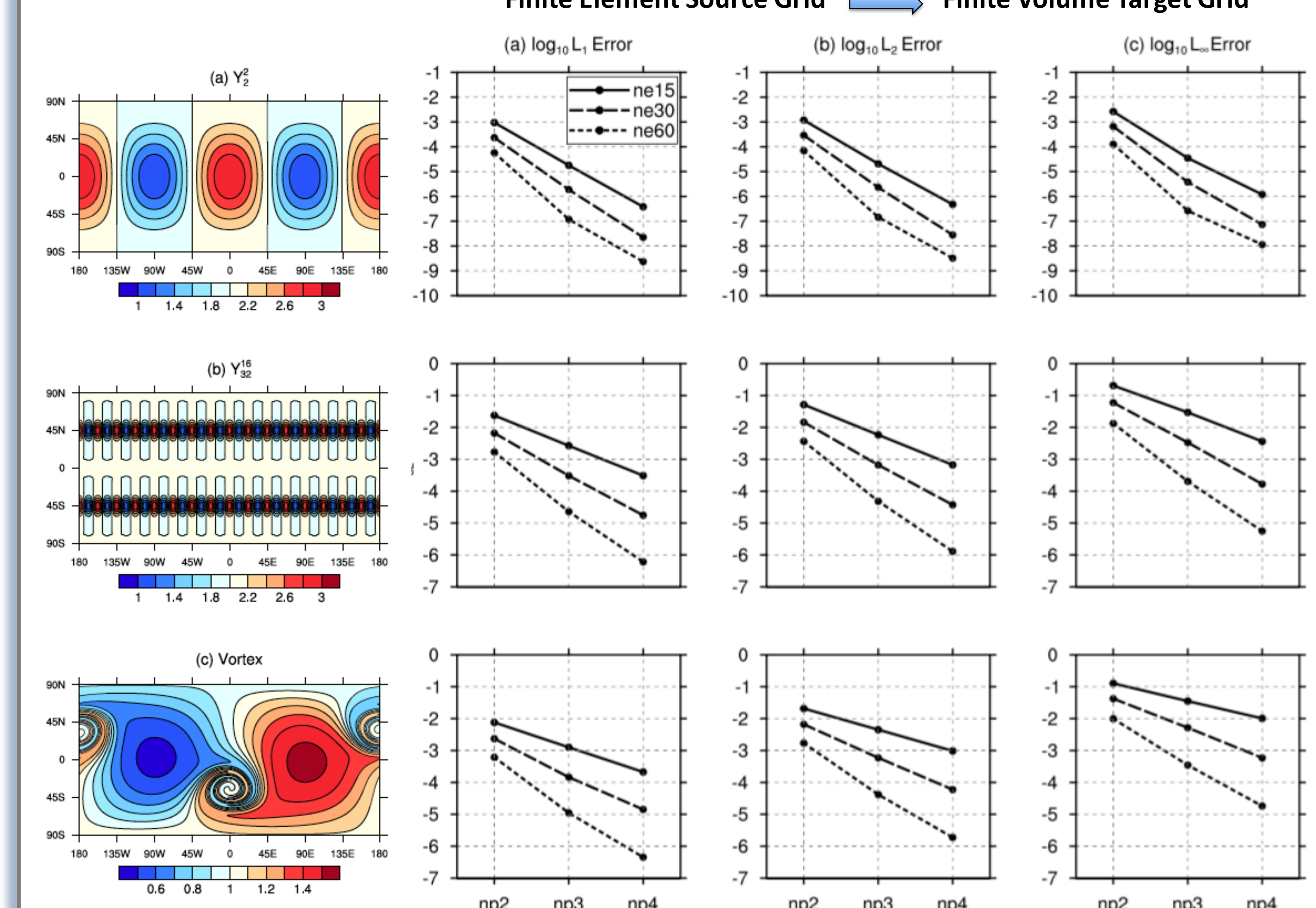


Figure (Above): Standard L_1, L_2 and L_∞ error norms reported for conservative and consistent remapping of the three idealized fields from the cubed-sphere mesh to the 1° great circle latitude-longitude mesh for cubed-sphere resolutions ne = 15, 30, 60 and for three finite element orders of accuracy np = 2, 3, 4.

References

- Ullrich, PA and MA Taylor (2015) "Arbitrary-Order Conservative and Consistent Remapping and a Theory of Linear Maps, Part 1" *Mon. Weather Rev.*, doi: 10.1175/MWR-D-14-00343.1.
- Ullrich, PA, D Devendran and H Johansen (2015) "Arbitrary-Order Conservative and Consistent Remapping and a Theory of Linear Maps, Part 2" *Mon. Weather Rev.* (Under Revision)

TempestExtremes

With Josephine Fong[1], Marielle Pinheiro[1], Michael Wehner[3], Prabhat[3], Kevin Reed[4], Colin Zarzycki[5]
[2] Sandia National Laboratories [3] Lawrence Berkeley National Lab
[4] Stony Brook University, New York [5] National Center for Atmospheric Research

Motivation

The next century will see unprecedented changes to the climate system that are particularly apparent to the general population via extreme weather events. Time series of the frequency, magnitude and other characteristics of these extreme weather events over the past century are not well-measured. TempestExtremes aims to quantify climate change effects on a broad set of extreme weather events, including tropical cyclones (TCs), extratropical cyclones (ETCs), atmospheric blocks, atmospheric rivers, temperature extremes and precipitation extremes.

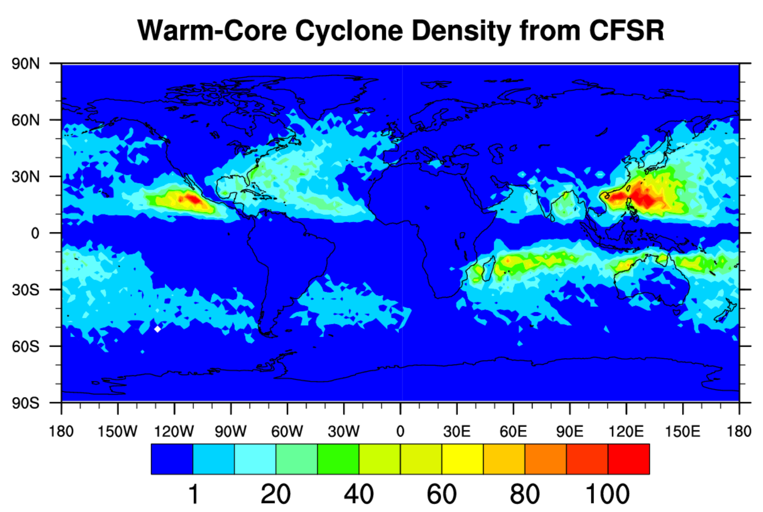


Figure (Above): Tropical cyclone (TC) densities obtained from the candidate detection and trajectory stitching algorithms applied to the CFSR Reanalysis.

This software consists of a suite of flexible detection and characterization algorithms developed for processing large climate datasets. This package uses an algorithmic framework known as "MapReduce" to first detect candidate events at individual times using specified criteria. Stitching is then used to assess the evolution of related detections over time. The result is an objective calculation of the climate indicator that can be automated and parallelized for multiple datasets.

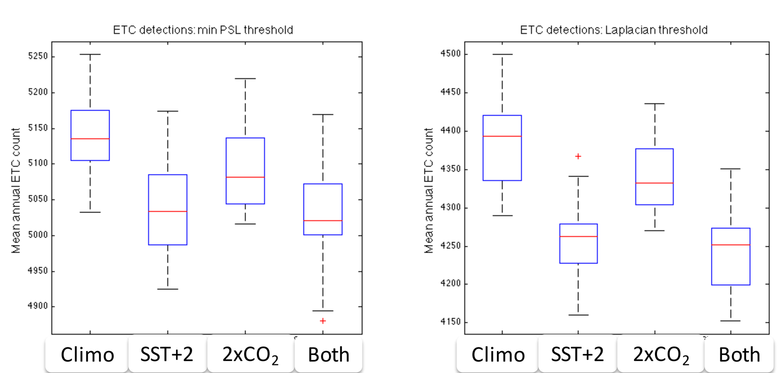


Figure (Above): Extratropical cyclone (ETC) counts obtained under CLIVAR emission scenarios showing a decrease in ETC numbers under future static climate scenarios. Left plot shows ETCs defined only by sea level pressure (SLP) minimum. Right plot shows ETC detections with SLP minimum and a Laplacian threshold.

This software is being developed in conjunction with the Toolkit for Extreme Climate Analysis.

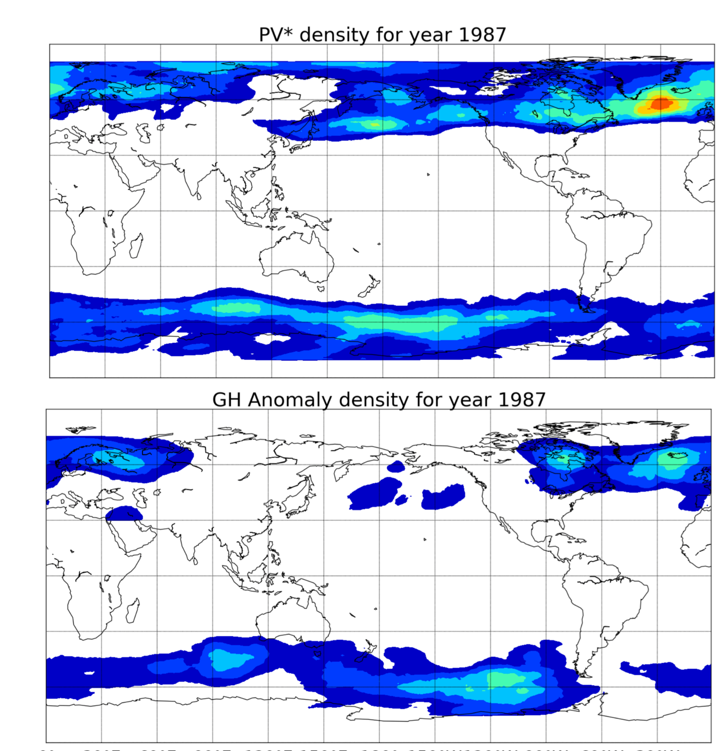


Figure (Above): Atmospheric blocks as indicated by (top) the Schwierz et al. blocking criteria and (bottom) the Dole and Gordon blocking criteria. Grid points are stitched in space to obtain blocking regions, which are in turn stitched in time to obtain space-time blocks. These features can then be individually quantified and characterized.

References

- Schwierz, C, M Croci-Maspoli, and HC Davies (2004) "Perspicacious indicators of atmospheric blocking." *Geophysical Research Letters* 31 (6).
- Pelly, JL, and BJ Hoskins (2003) "A new perspective on blocking." *Journal of the Atmospheric Sciences* 60 (5): 743-755.
- Neu, Urs, et al. (2013) "IMILAST: A community effort to intercompare extratropical cyclone detection and tracking algorithms." *Bulletin of the American Meteorological Society* 94 (4): 529-547.
- Rübel, O, S Byna, K Wu, F Li, M Wehner and W Bethel (2012). "TECA: A parallel toolkit for extreme climate analysis." *Procedia Computer Science* 9: 866-876.

Software

TempestDynamics
git clone https://github.com/paullric/tempestmodel.git

TempestRemap
git clone https://github.com/paullric/tempestremap.git

TempestExtremes
git clone https://github.com/paullric/tempestextremes.git

Contact

paullrich@ucdavis.edu