Space-Time Structure of Diabatic Heating in the Atmosphere

A Useful Diagnostic for Both Weather and Climate
(A few examples shown)

"Apparent Heating" Method Applicable to Reanalysis and Models

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Acknowledgements: Sarah-Jane Lock (ECMWF), Daniela Domeisen (ETH, Zurich), Franco Molteni (ECMWF) and Priyanka Yadav (NASA)

Why is Diabatic Heating Important?

Tropical Forcing of Extra-Tropics in the Stationary Wave Paradigm:
Heating → Rossby Wave Source → Response

Development of baroclinic systems is influenced by tropical heating;
Configuration of Atlantic Storm Tracks

How important is the vertical structure of heating?

GEORGE MASON UNIVERSITY

COLA

ECMWF

Can we already assess diabatic heating directly from observations?

Yes – From precipitation the integral of latent heating can be estimated

Vertical structure and other forms of heating not accessible – also precip is hard to measure!

Vertical structure of latent heat can be derived from Satellite data (TRMM) for a limited number of years

Methods rely on assigning vertical structures to different types of precipitation (Shige at al. 2004)

The Global Precipitation Measurement Misson (NASA) measures precipitation globally:

latent heat structure is then derived using a model

Past comparisons of reanalysis heating to results from field campaigns in the tropics rely on essentially the same Apparent Heating technique

(Hagos et al. 2010)

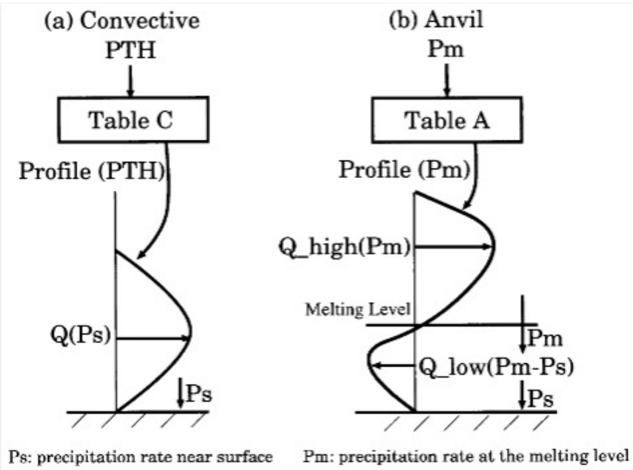


FIG. 8. Diagram showing the procedure for deriving latent heating profiles using the SLH algorithm. See the text for details.

Hagos. S. and co-authors, 2010 : Estimates of Tropical Heating Profiles: Commonalities and Uncertainties. *J. Clim.*, **23**, 542-558.

Shige, S., Y. N. Takayabu, W.-K. Tao and D. E. Johnson, 2004: Spectral Retrieval of Latent Heating Profiles from TRMM PR Data. Part I: Development of a Model—Based Algorithm, *J. Appl. Meteor.*, **43**,1095-1203.

“Apparent Heating” Method to Diagnose total diabatic heating in the global domain from the thermodynamic equation

$$T\,\frac{dS}{dt} = Q$$

$$S = C_p \ln \theta$$

Here T is temperature, S entropy, Q the *rate* of diabatic heating, C_p the specific heat at constant pressure and Θ is potential temperature.

The *total* time derivative d/dt is evaluated in pressure coordinates.

Data Required:

- **Fields of (u, v, T, ω) on pressure levels**

You can use other vertical coordinates
Comparison of models or models/reanalysis requires consistency

- **High Resolution Data in (x,y,p,t)**

In the past, small scale contributions were not accounted for using this method
Reanalyses and forecast models are becoming much higher resolution in space and available at finer time intervals

Some important Notes:

- **For reanalyses, this method uses *only analyzed fields***

Distinct from using diabatic heating in the short-range forecasts used to create the reanalyses.

- **High resolution pressure level data available for many models and for reanalyses – comparison is easy.**

Some but not all models allow you to directly save diabatic temperature tendencies but often this is not available (e.g. IFS of ECMWF)

- **The total diabatic heating is diagnosed (not just the latent heating)**
  - **Heating due to radiation, ozone, gravity waves, turbulence and diffusion all included**

- **Stratospheric Heating can be Estimated**

- **The vertical and temporal structure can be well-resolved**

Application to Predictability of Response to the Madden-Julian Oscillation

Diabatic Heating is very intermittent in space and time

We expect differences in the detailed structure and evolution of tropical heating *even among episodes of any given phase of the MJO.*

Does this intrinsic uncertainty affect the predictability of the Rossby Wave Source and the Extra-Tropical Response ?

Straus, D. M., D. I. V. Domeisen, S.-J. Locke, F. Molteni and P. Yadav, 2023: Intrinsic Predictability Limits Arising from Indian Ocean Madden-Julian Oscillation (MJO) Heating: Effects on Tropical and Extratropical Teleconnections. *Weather and Climate Dynamics*, **4**, 1001-1008. https://doi.org/10.5194/wcd-4-1001-2023

Application to Predictability of Response to the Madden-Julian Oscillation

Experiments designed specifically to address this question run by Sarah-Jane Lock using IFS* of ECMWF (fully coupled model, atmospheric resolution of 36 km, 91 vertical levels)

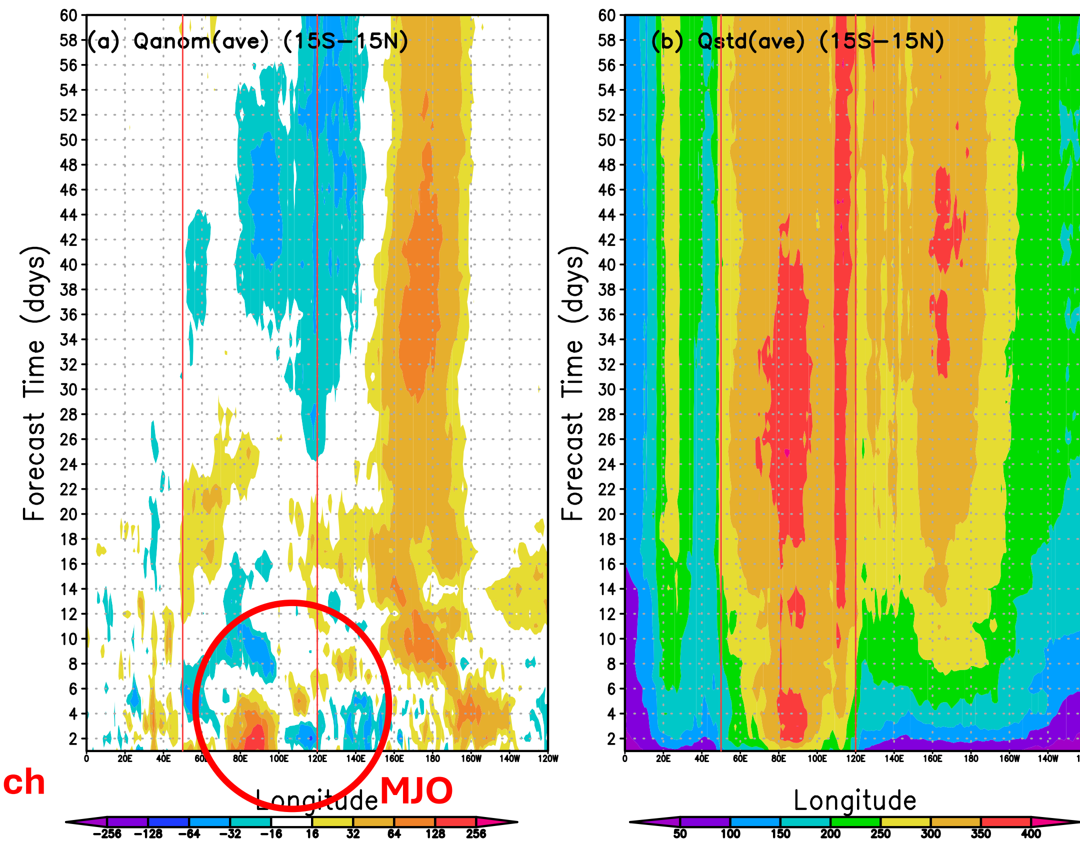
- **60-day reforecasts initialized from 13 initial conditions associated with MJO phase 2-3**
- **For each IC, 51 ensemble member forecast suite was run *with identical ICs for all members***
- **The stochastic perturbation scheme (SPPT) [which is a standard component of IFS] is confined to the tropical Indian – West Pacific Ocean region**
- **The only cause for divergence among ensemble members for a given IC is the perturbations to heating (+ other fields affected by SPPT) in the tropical Indian-Ocean !!**

Straus, D. M., D. I. V. Domeisen, S.-J. Locke, F. Molteni and P. Yadav, 2023: Intrinsic Predictability Limits Arising from Indian Ocean Madden-Julian Oscillation (MJO) Heating: Effects on Tropical and Extratropical Teleconnections. *Weather and Climate Dynamics*, **4**, 1001-1008. https://doi.org/10.5194/wcd-4-1001-2023

(a) Evolution of the <u>ensemble mean</u> anomaly of diabatic heating anomaly Q (Wm^{-2})

(b) Evolution of the <u>ensemble standard deviation</u> of diabatic heating anomaly Q (Wm^{-2})

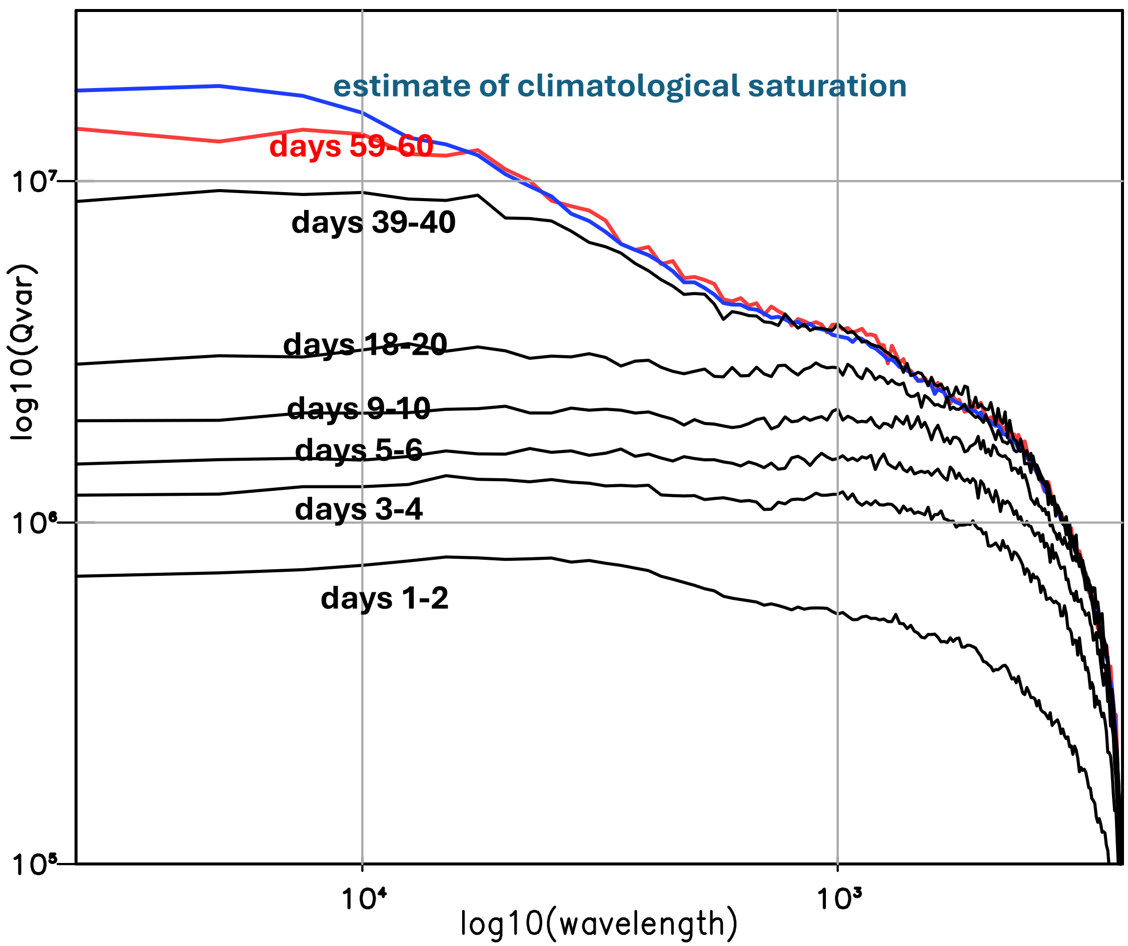
Q = diabatic heating anomaly, vertically integrated, averaged 15∘ S–15∘ N



The red lines indicate the range of longitudes over which stochastic parametrization (SPPT) was applied

Zonal wavenumber spectra of error (ensemble spread) in tropical diabatic heating (850-400 hPa) for various forecast times.

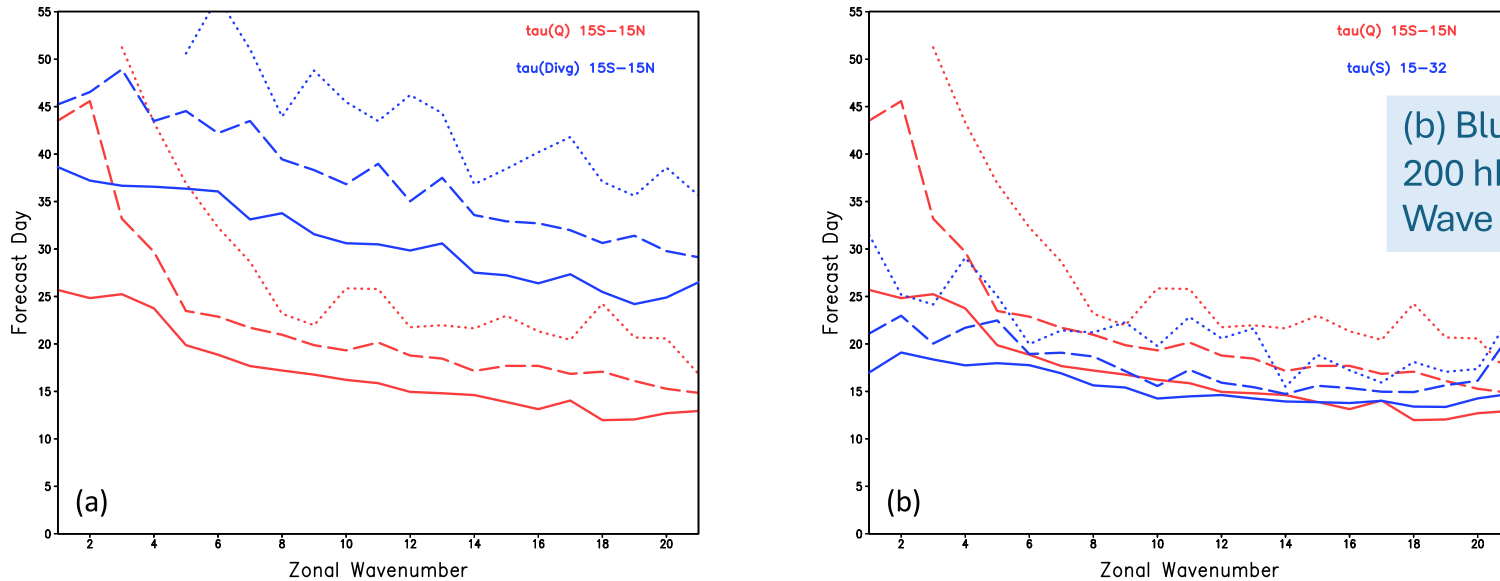
The heating was averaged over latitudes 15◦ S–15◦ N.



(a) The forecast day τ at which the error variance of heating Q (averaged 15S–15N) reaches a fraction f_τ of the external error for f_τ = 0.50, 0.70 and 0.90 shown in solid, dashed and dotted red lines. The blue lines show τ for the 200 hPa divergence averaged over 15S–15N.

(b) τ for the error variance in Q as in (a) along with τ for the Rossby wave source (S) averaged over 15–32° N shown with blue lines.

(a) Blue curves: Divergence (200 hPa)



(b) Blue curves: 200 hPa Rossby Wave Source

Predictability Times as a Function of Zonal Wavenumber of error reaching 50% (solid), 70% (dashed) and 90% (dotted) of saturation. Heating shown in red: 90% limit never reached!

Use of Diabatic Heating to Monitor Changes in Model Behavior due to Parameterization Change

ECMWF is in the process of changing the Stochastic Peturbations to Tendencies from physical parameterizations

FROM

"SPPT" in which the output of the tendencies is stochastically perturbed

TO

"SPT" in which perturbations are constructed in such a way that the internal consistency of the physical parametrization schemes is preserved.

(Energy conservation better maintained)

How does this affect the diabatic heating?

Simon T. K. Lang, Sarah-Jane Lock, Martin Leutbecher, Peter Bechtold, Richard M. Forbes, 2021: Revision of the Stochastically Perturbed Parametrisations model uncertainty scheme in the Integrated Forecasting System. Quart. *J. Royal Meteor. Soc.*, **147**,1364-1381.

To assess the changes in the model heating:

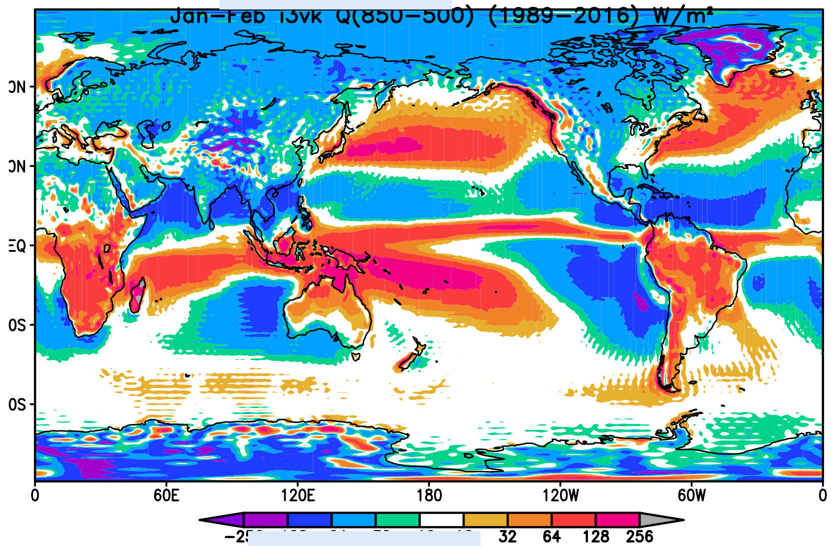
Two sets of two-month forecasts were run:
(1) uses SPPT scheme
(2) uses new SPP scheme

ICs: 01 January1989 – 2016
Ensemble Size: Ctl run + 9 perturbations
Length: 60 days.

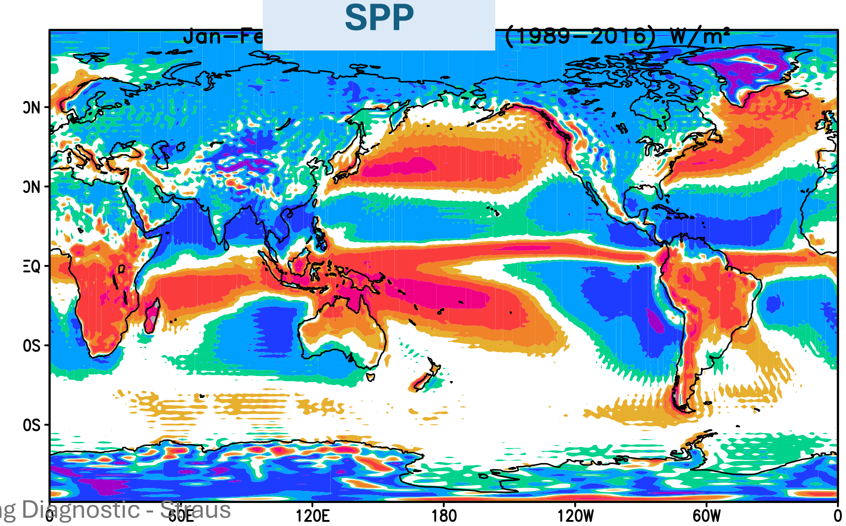
We show Jan-Feb time averaged heating for the layer 850-500 hPa for both In Wm^{-2})

Very similar patterns are seen.

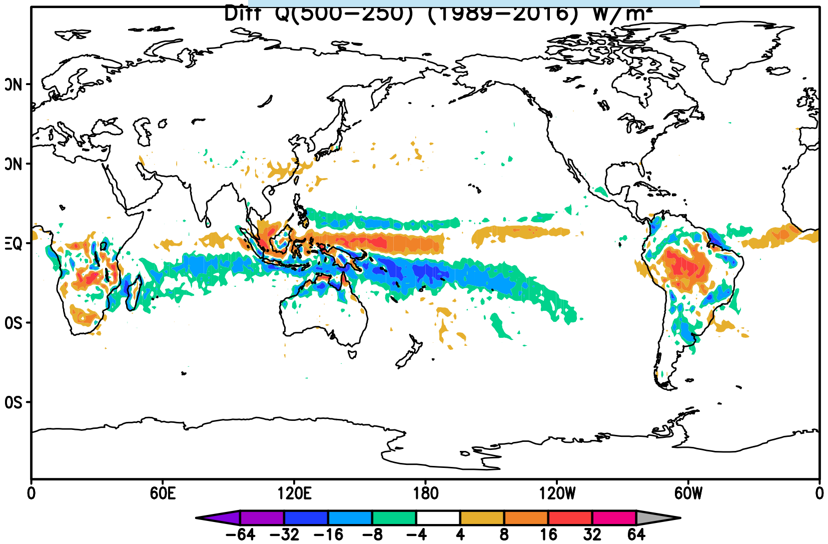
SPPT



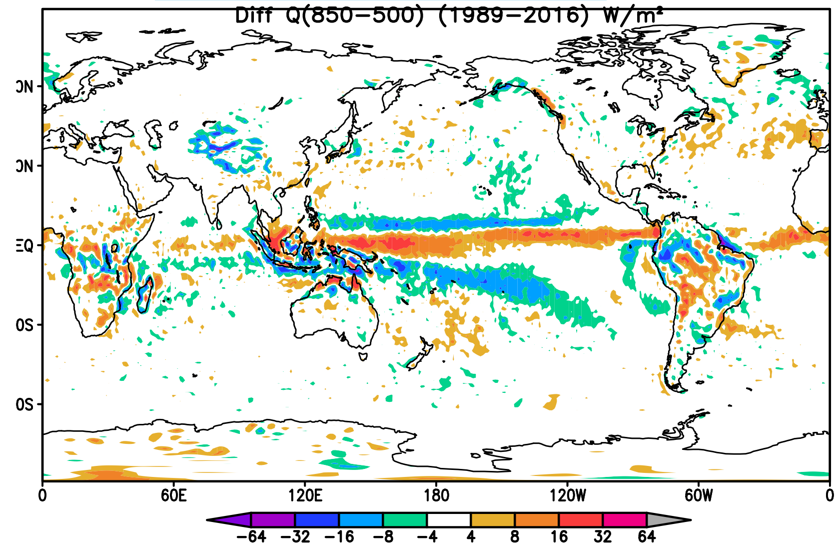
SPP



500-200 hPa Layer



850-500 hPa Layer



Differences in Diabatic Heating (SPP minus SPPT) for two vertical layers
(all differences shown are significant at the 95% level)

- **Tighter representation of the ITCZs in both oceans**
- **Greater heating over Amazon particularly at upper levels**
- **Greater heating over downstream portion of the Atlantic Storm Track.**

Ongoing and Future Work

Extension to Isentropic Coordinates (?)

Comparing Vertical Structure of Heating in ERA5, MERRA2 JRA 3Q

Investigating Relationship of Warm Conveyor Belt Diabatic Heating to Storm Track Configuration