On the role of the tropics in global predictability

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HAPPY ANNIVERSARY, ECMWF!

Outline

- Recent results on tropics-extratropics coupling (Subtropical dynamics)
- Tropical analysis and short-range forecast uncertainties
- On under-observed tropical circulation
- Effects of tropical initial state on extratropical predictability

*Recent results are based on ESA-funded "Aeolus+Processes" project with the ECMWF,
and the PhD research projects of Katharina M. Holube, Sandor I. Maho and Chen Wang at UHH*

Main Points

Understanding practical predictability is closely linked to understanding dynamics. Tropical circulation and predictability are influenced by subtropical dynamical processes.

Replacing nudging with tropical and extratropical (or midlatitude) observation denial OSEs – TOSE and MOSE – reveals under-observed state of the tropics.

The background wind (i.e. critical latitude) in the subtropics determines the poleward propagation of the signals from the tropical initial state. Synoptic scales are the most relevant for extratropical predictability.

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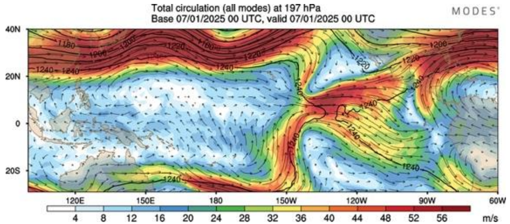
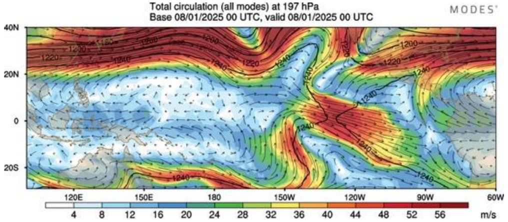
Illustrating the challenge of understanding tropical predictability: an example of recent tropical weather

Horizontal circulation at a level near 200 hPa in the operational ECMWF analyses

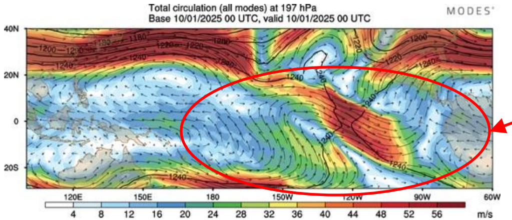
From http://modes.cen.uni-hamburg.de

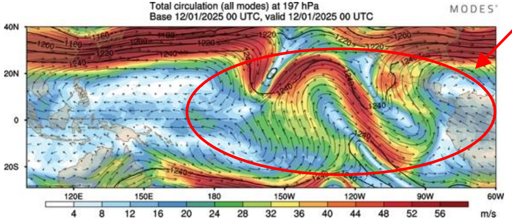
Analyses

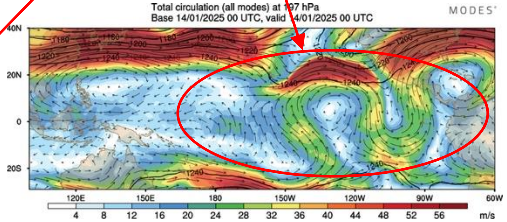


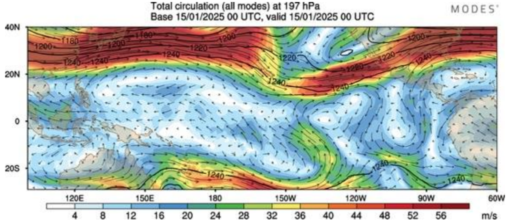


What process is this?

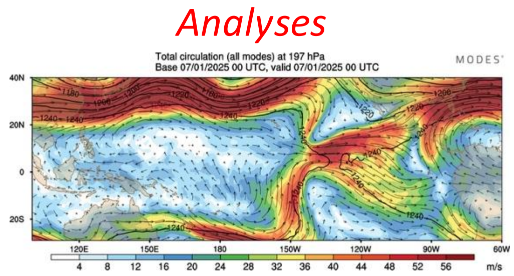


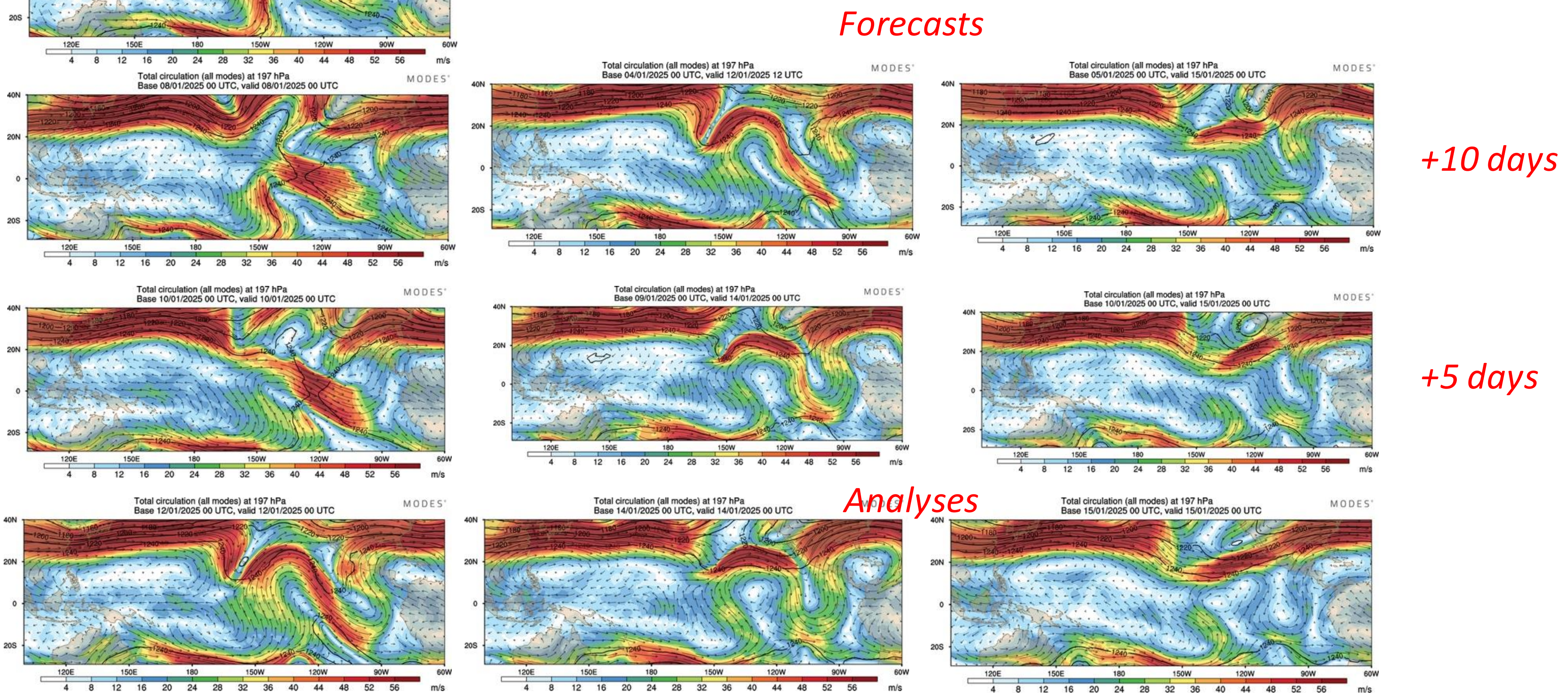






Illustrating the challenge of understanding tropical predictability: an example of recent tropical weather

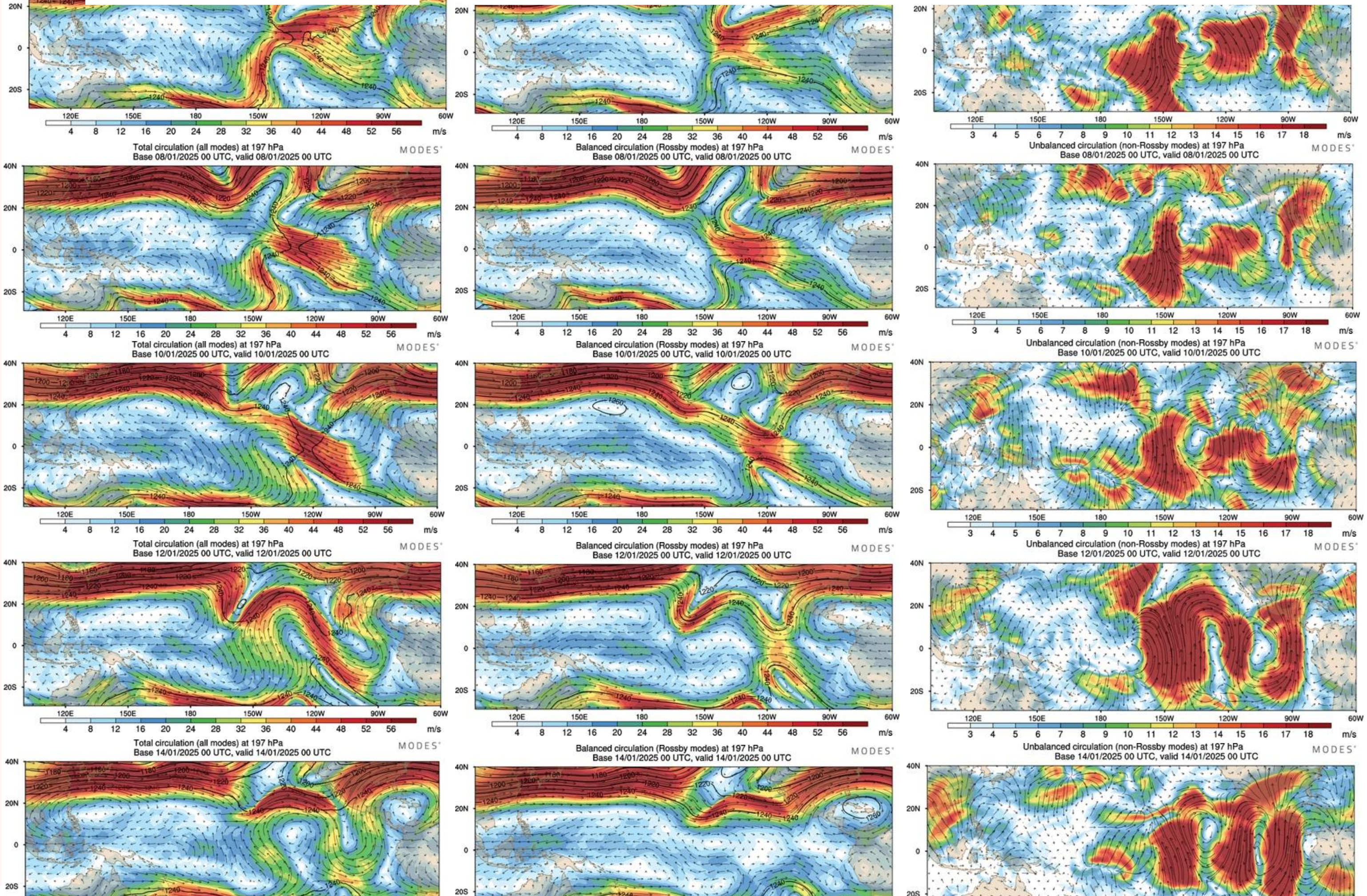




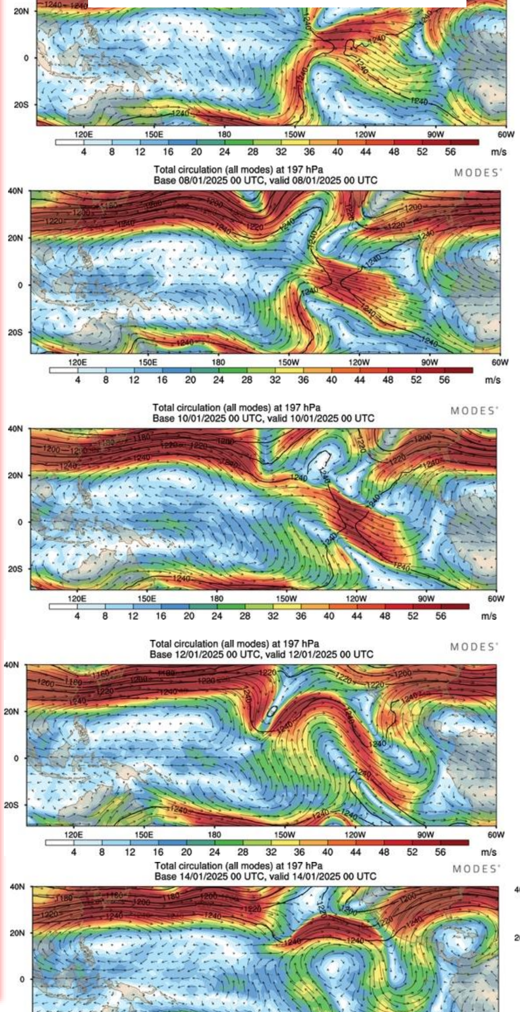
Total

Linear Rossby waves

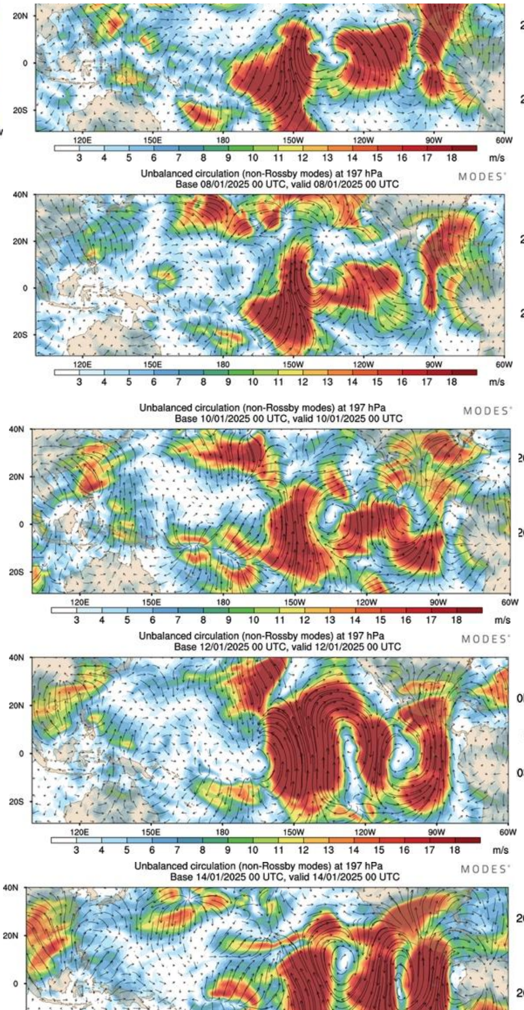
Linearly unbalanced



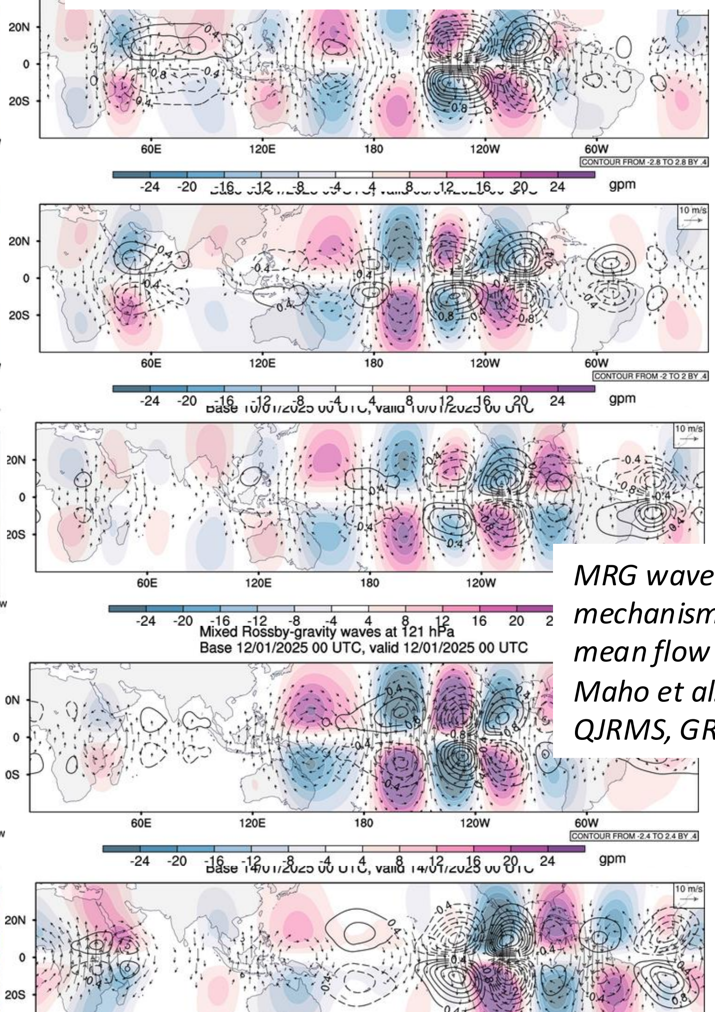
Total



Linearly unbalanced



Mixed Rossby-gravity waves



MRG wave excitation mechanism by wave-mean flow interactions.
Maho et al., 2024 QJRMS, GRL

Main Points

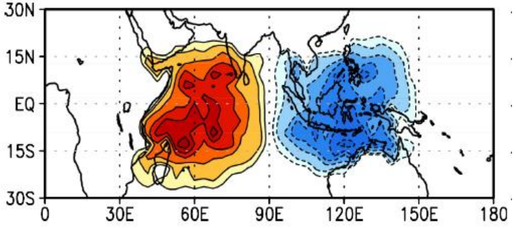
Understanding practical predictability is closely linked to understanding dynamics. Tropical circulation and predictability are influenced by subtropical dynamical processes. Effects of the tropics on extratropics involve subtropical dynamics.

Replacing nudging with tropical/extratropical observation denial OSEs (TOSE/MOSE) reveals under-observed state of the tropics.

The background wind (i.e. critical latitude) determines the tropical synoptic scale Rossby waves as most relevant for extratropical predictability.

Tropical effects on extratropics: via the Rossby wave source

Heating anomaly (every 1 K)

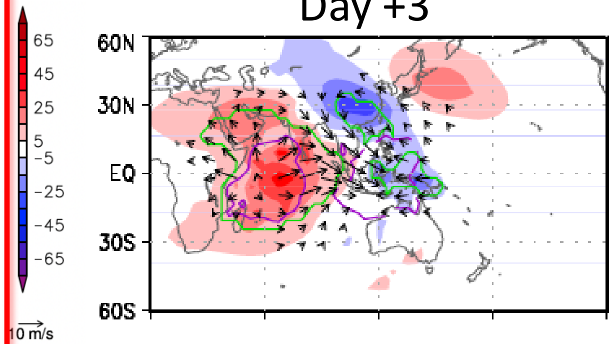


$$\left(\frac{\partial T}{\partial t}\right)_{pert}(\lambda,\phi,\sigma) = F_{SST} H_{pert}(\lambda,\phi)\left(\frac{\partial T}{\partial t}\right)_{CC}(\phi,\sigma)$$

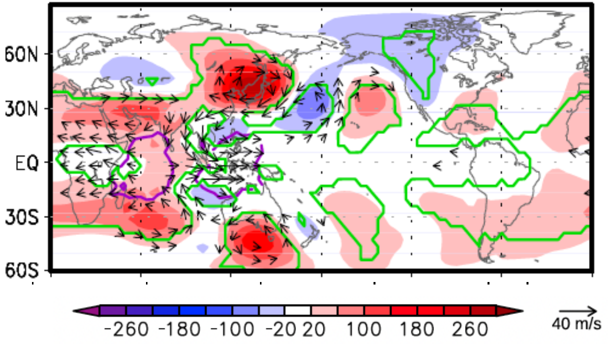
tendencies coming from the large-scale condensation and convection parameterization

Circulation anomaly at 200 hPa in boreal winter

Day +3



Day +14



Moist processes enhance the circulation effects produced in adiabatic experiments

From Kosovelj et al., 2019, JAS with F. Molteni

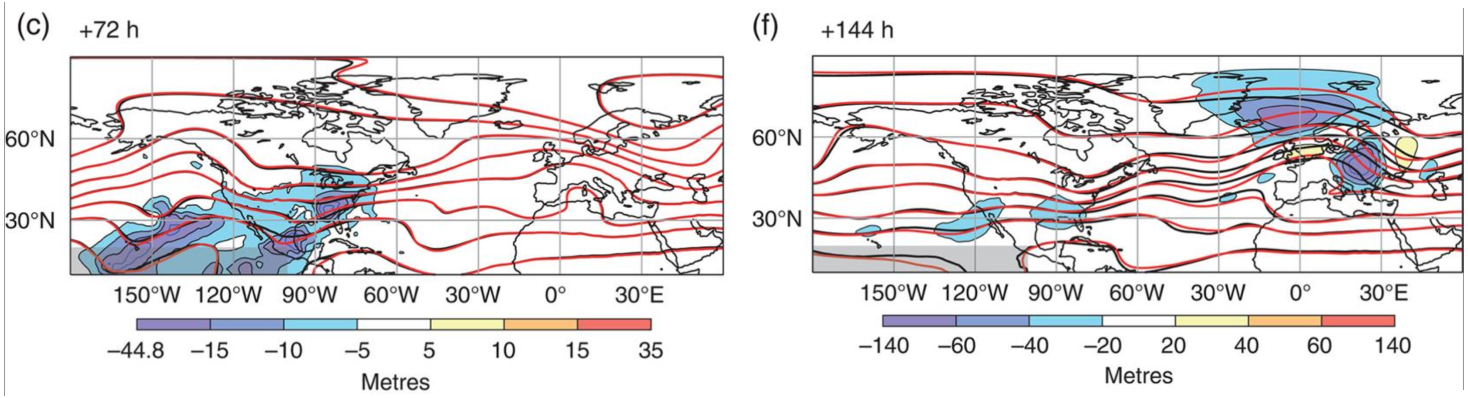
Tropical effects on extratropical predictability and extratropical effects on tropical predictability

$$\frac{\partial u}{\partial t} = -\frac{1}{a\cos\varphi}\frac{\partial \Phi}{\partial \lambda} + 2\Omega \sin\varphi\, v - \mathbf{V}_H \cdot \nabla u - \omega \frac{\partial u}{\partial p} + \frac{\tan\varphi}{a} uv + S_u \underbrace{- \alpha(u - u^*)}$$

Relaxation or nudging term

Ferranti et al., 1990, JAS

Nudging the tropics disables studying of tropical and subtropical processes in the simulations

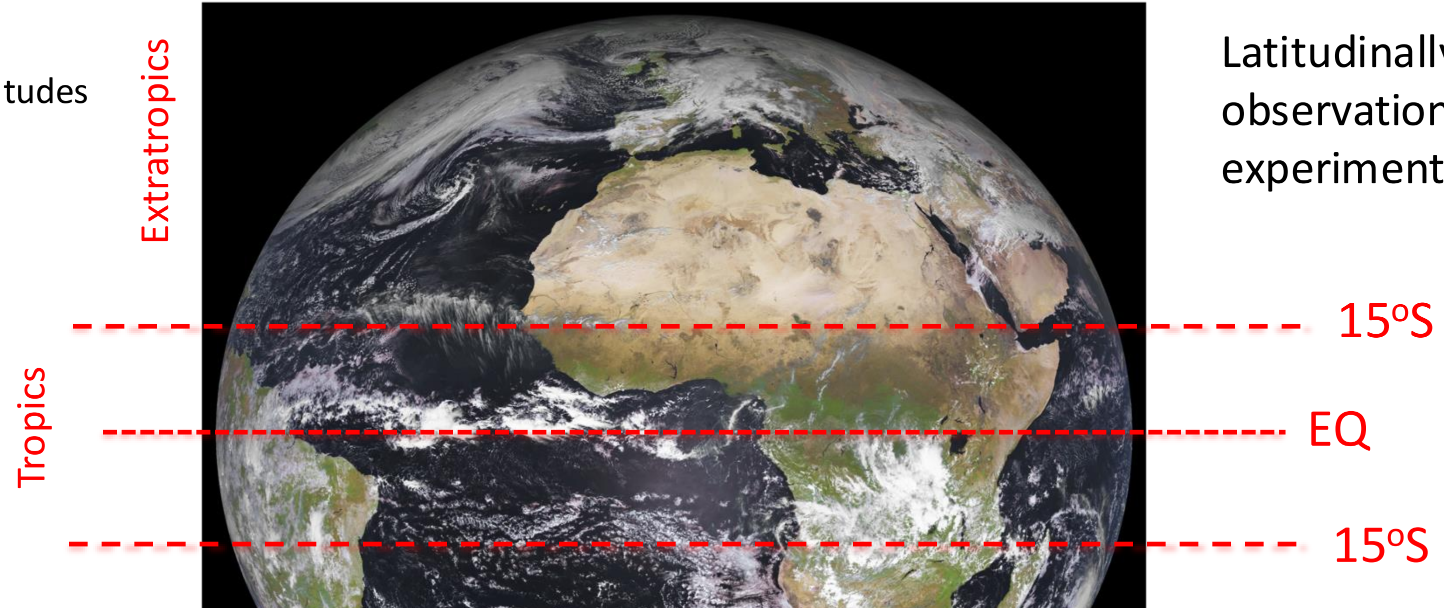


Figures from Magnusson, 2017, QJRMS

Nudging of vorticity, divergence and temperature in the ECMWF model

OSEs using observations within the tropics or extratropics: TOSE and MOSE (or TOSSE and MOSSE)

T – tropics
M – midlatitudes



Latitudinally-limited observation denial experiments

With the ECMWF system: 5-month TOSE and MOSE 12/2022-04/2023
Collaboration with S. Healy and G. De Chiara

Perfect-model TOSE and MOSE with the DART/CAM system of NCAR
Collaboration with J. Anderson and K. Reader

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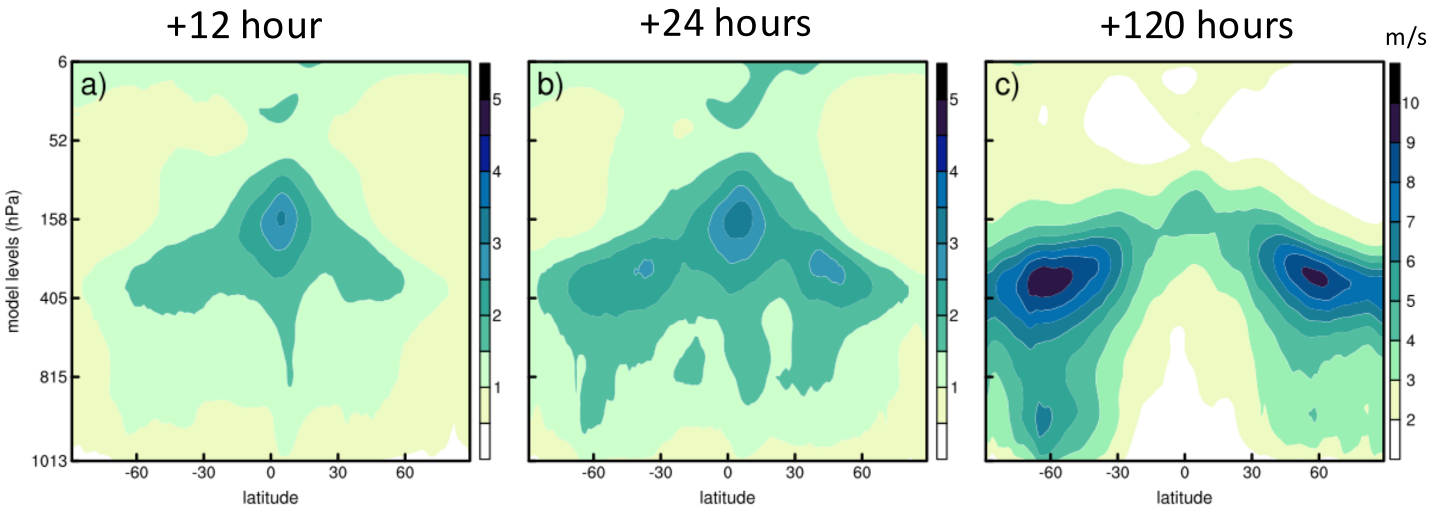
Progress in understanding tropical analysis and forecast uncertainties has been slow. Replacing nudging with tropical/extratropical observation denial OSEs (TOSE/MOSE) reveals under-observed state of the tropics.

The background wind (i.e. critical latitude) in the subtropics determines the poleward propagation of the signals from the tropical initial state. Synoptic scales are the most relevant for extratropical predictability.

Zonally-averaged forecast-error statistics derived from the ECMWF ensemble forecasts



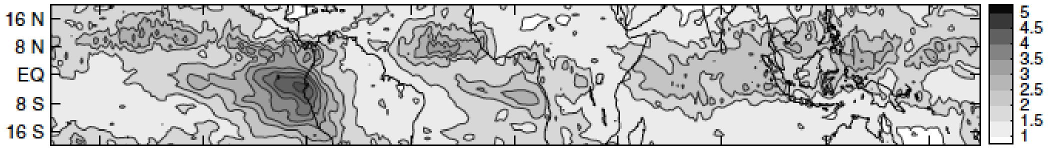
Data from May 2015, Cy41r1, ~150 hPa level

Zonal wind ensemble standard deviation

From Tellus A, 2017

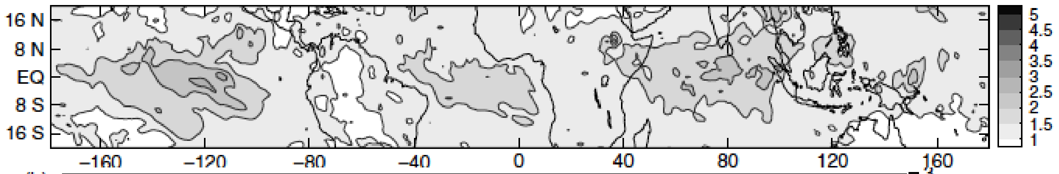
Ensemble-derived uncertainties in analyses and short-range forecasts

Zonal-wind ensemble standard deviation

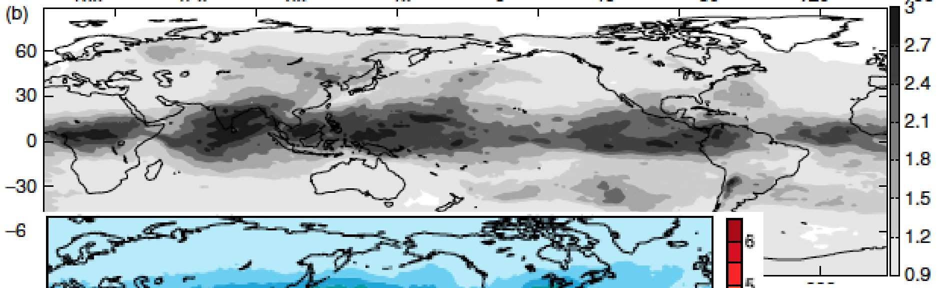


Data from Oct 2000, Cy23r4, ~200 hPa

From QJRMS, 2005, 2007
with E. Andersson, M. Fisher and A. Untch

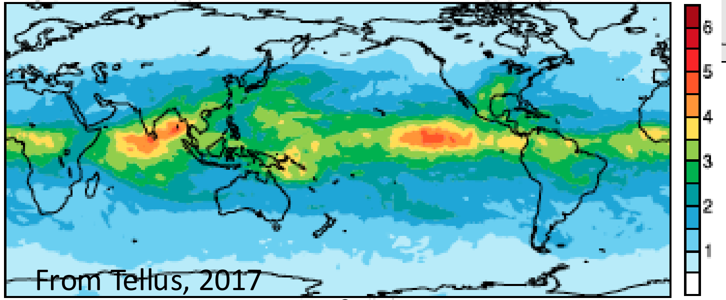


Data from Sep 2003, Cy28r4, ~200 hPa



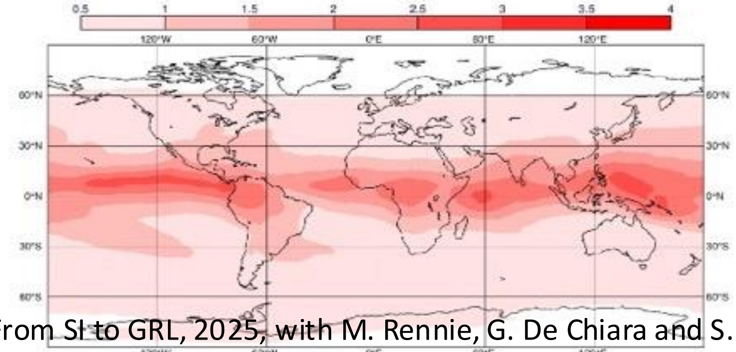
Data from July 2007, Cy32r3, ~200 hPa

From QJRMS, 2013, with L. Isaksen and D. Tan



From Tellus, 2017

Data from May 2015, Cy41r1, ~150 hPa

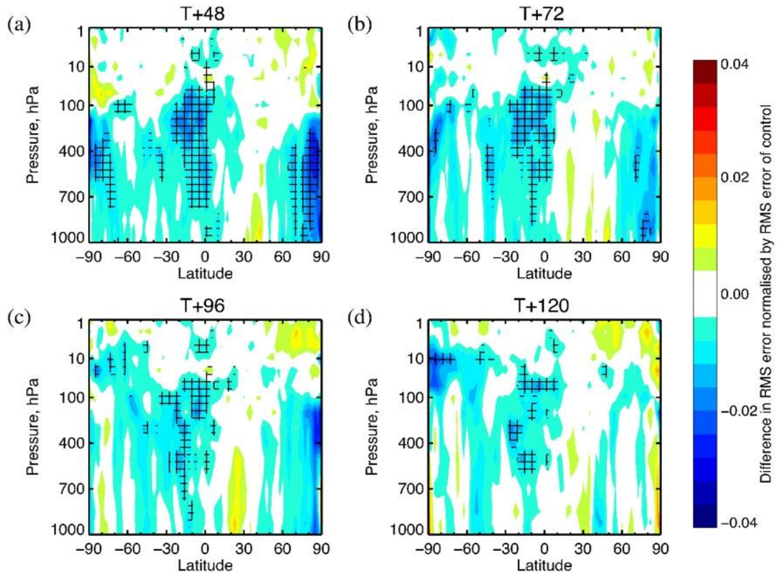


From SI to GRL, 2025, with M. Rennie, G. De Chiara and S. Healy

Data from June-Dec 2019, ~140 hPa

Lessons from the assimilation of ESA's Aeolus wind profiles

From Rennie et al., 2021, QJRMS



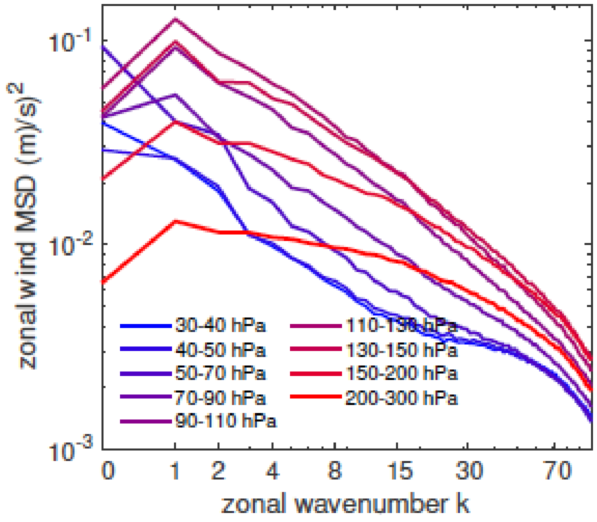
A special issue of QJRMS on Aeolus impacts in NWP models:
https://rmets.onlinelibrary.wiley.com/doi/toc/10.1002/(ISSN)1477-870X.aeolus

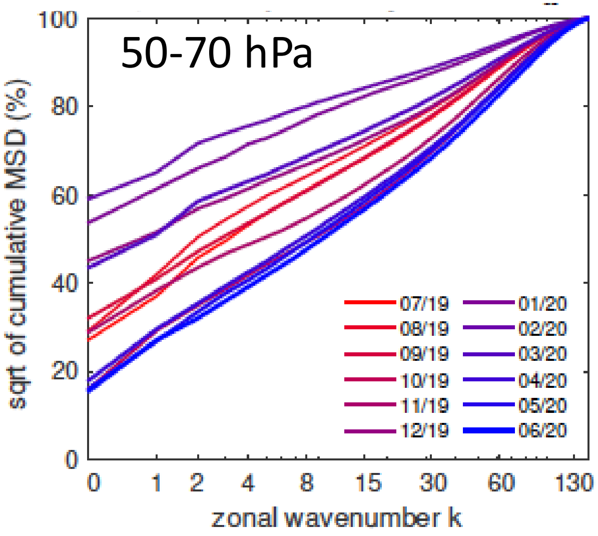
https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Aeolus/

What processes in the tropics have been corrected by Aeolus?

Scale-distribution of the effects of Aeolus wind assimilation

Scale, altitude and flow dependency





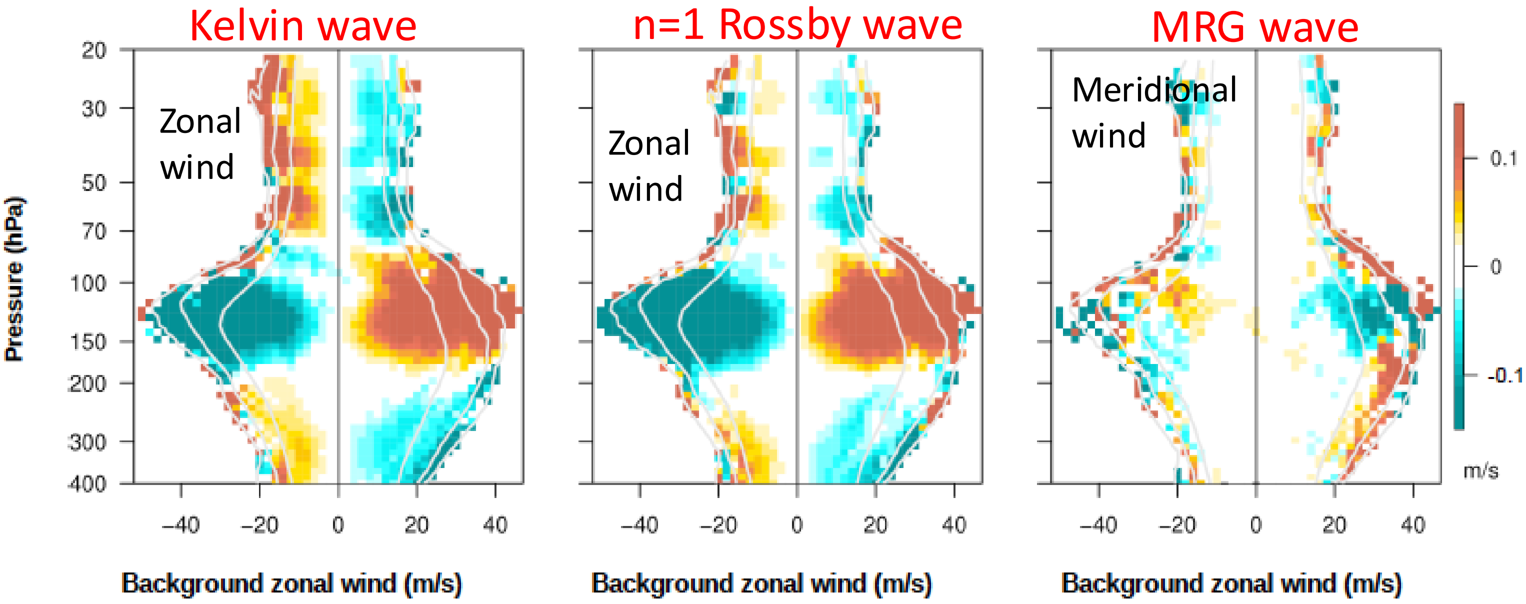
Mean square difference (MSD) of Aeolus – NoAeolus
Zonal wind MSD as a function of zonal wavenumber
Averaging over 07/2019-06/2020, 10°N-10°S
Different layers of deep tropics

From GRL, 2025, with
M. Rennie, G. De Chiara and S. Healy

- Largest effect on *k*=0 in the lower stratosphere: correction of shear lines of the QBO
- Relative scale distribution of the effect within the UTLS greatly varies with the flow
- Largest effect on the mean state in summer 2019 and during the QBO disruption
- Overall largest effect within in just above the tropopause – a critical layer for the upward propagating waves from the troposphere

Effects of Aeolus wind assimilation on equatorial waves: systematic effects

Aeolus-NoAeolus analyses



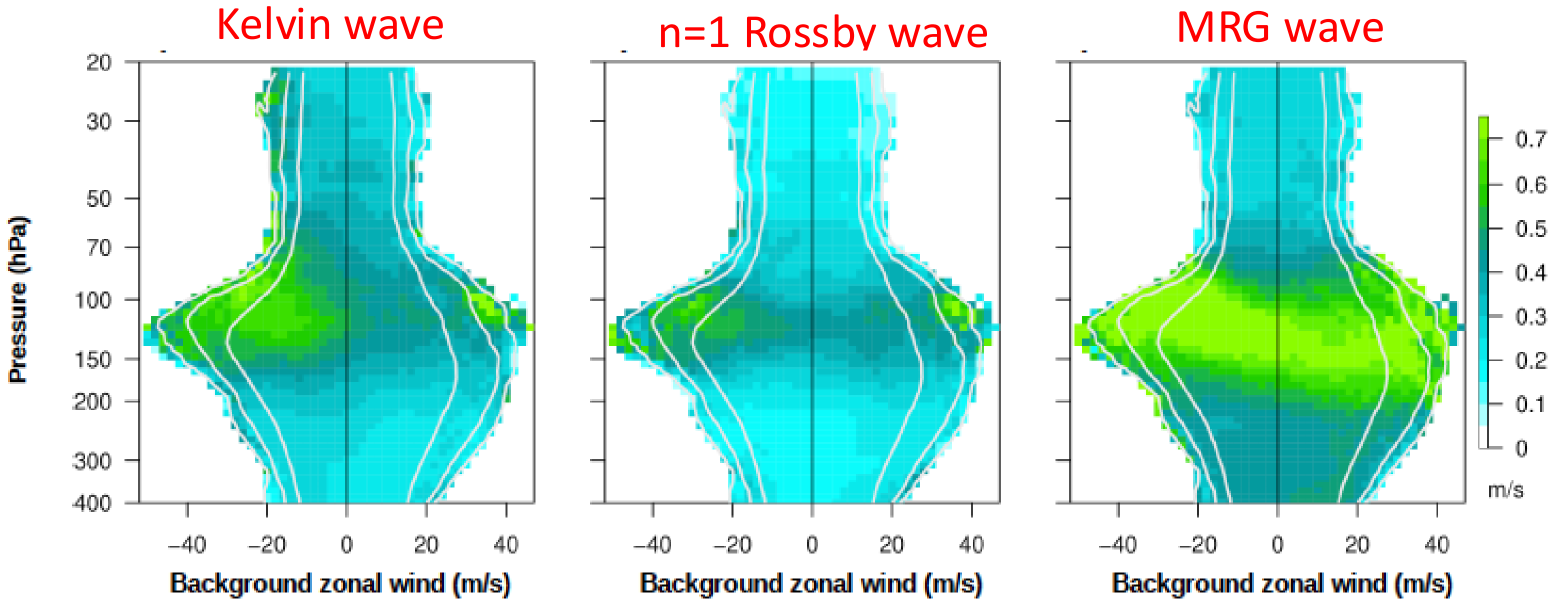
The assimilation of Aeolus winds aims at enhancing wave amplitudes in the TTL in both easterlies and westerlies

Period: 07/2019-06/2020

From GRL, 2025, with M. Rennie, G. De Chiara and S. Healy

Effects of Aeolus wind assimilation on equatorial waves: total effect (MSDs)

Aeolus-NoAeolus analyses



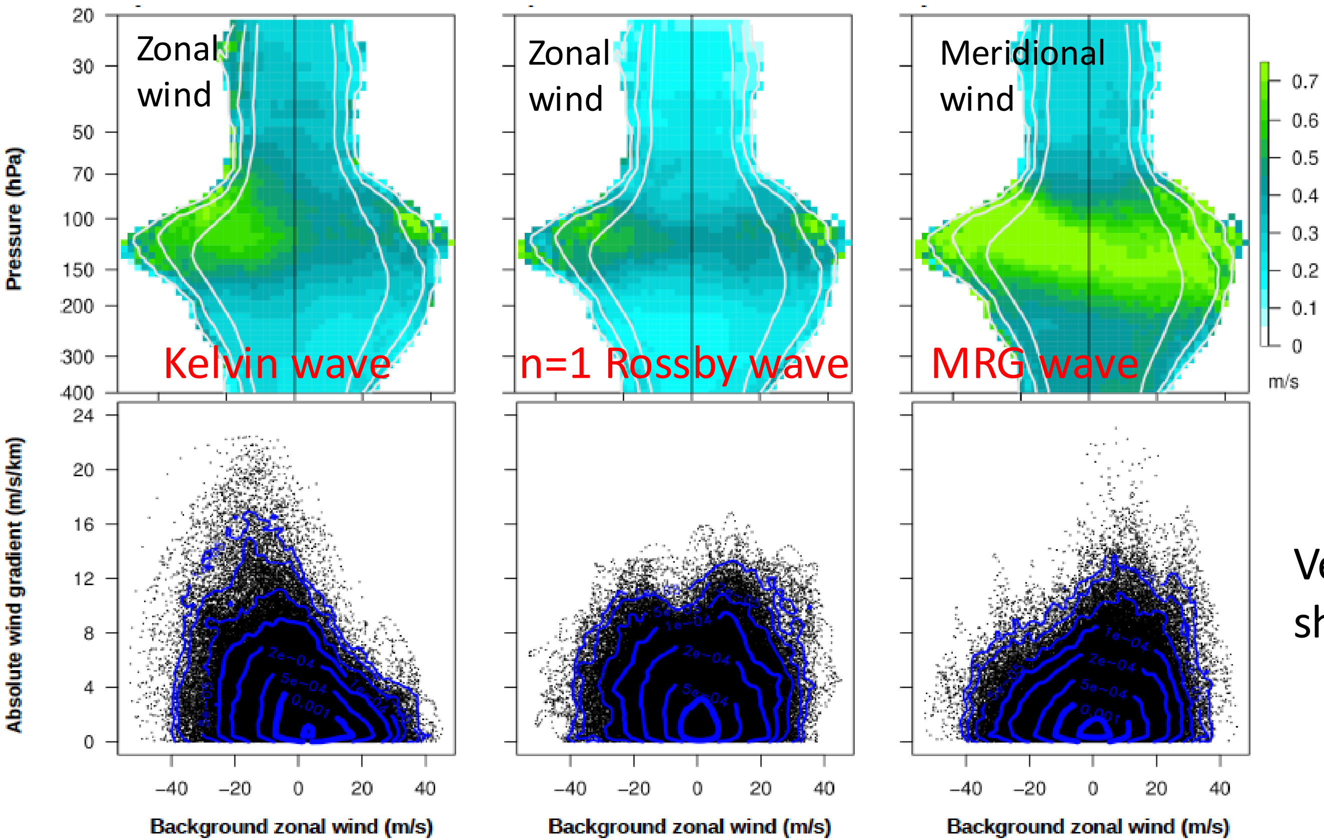
Period: 07/2019-06/2020

The equatorial wave zonal winds are enahnced stronger in easterlies, which, on avearge, exhibit larger shear.

From GRL, 2025, with M. Rennie, G. De Chiara and S. Healy

Effects of Aeolus wind assimilation on equatorial waves: total effect (MSDs) and vertical shear

Aeolus-NoAeolus analyses



MSDs

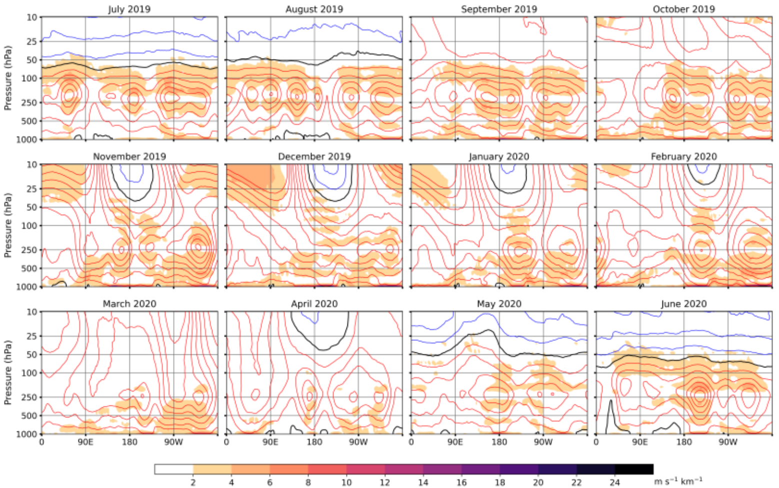
Vertical shear

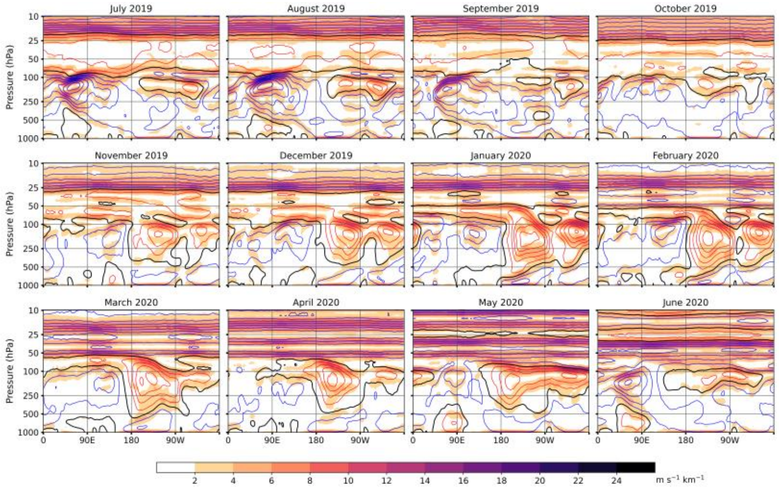
Period: 07/2019-06/2020

Linking effects of Aeolus winds with the background shear

Monthly mean zonal wind (isolines) and its shear (as absolute value, shades)

40° N - 50° N average





5° N - 5° S average

The largest wind shear is in the tropical UTLS: TEJ, the core of Pacific westerlies, and the QBO shear lines.

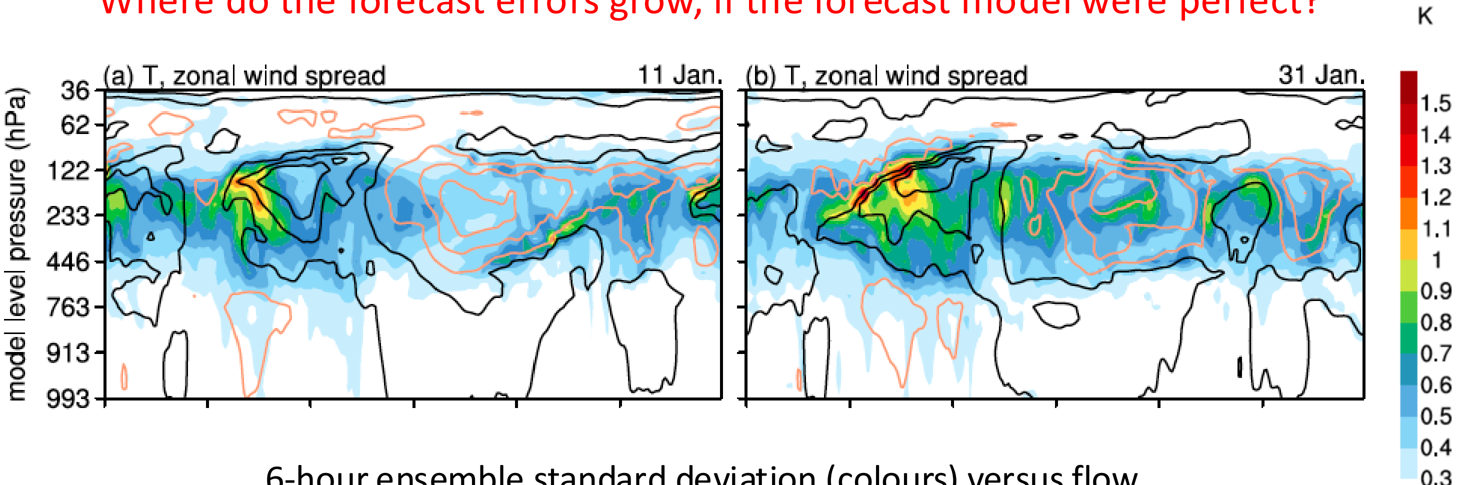
Project results highlight that it is not the wind field itself, but its vertical shear wrt variability that defines the usefulness of the wind profiles in the NWP.

From GRL, 2025, with M. Rennie, G. De Chiara and S. Healy

On the growth of short-term forecast uncertainties

A perfect-model, EnKF study of the relative value of wind and temperature observations

Where do the forecast errors grow, if the forecast model were perfect?



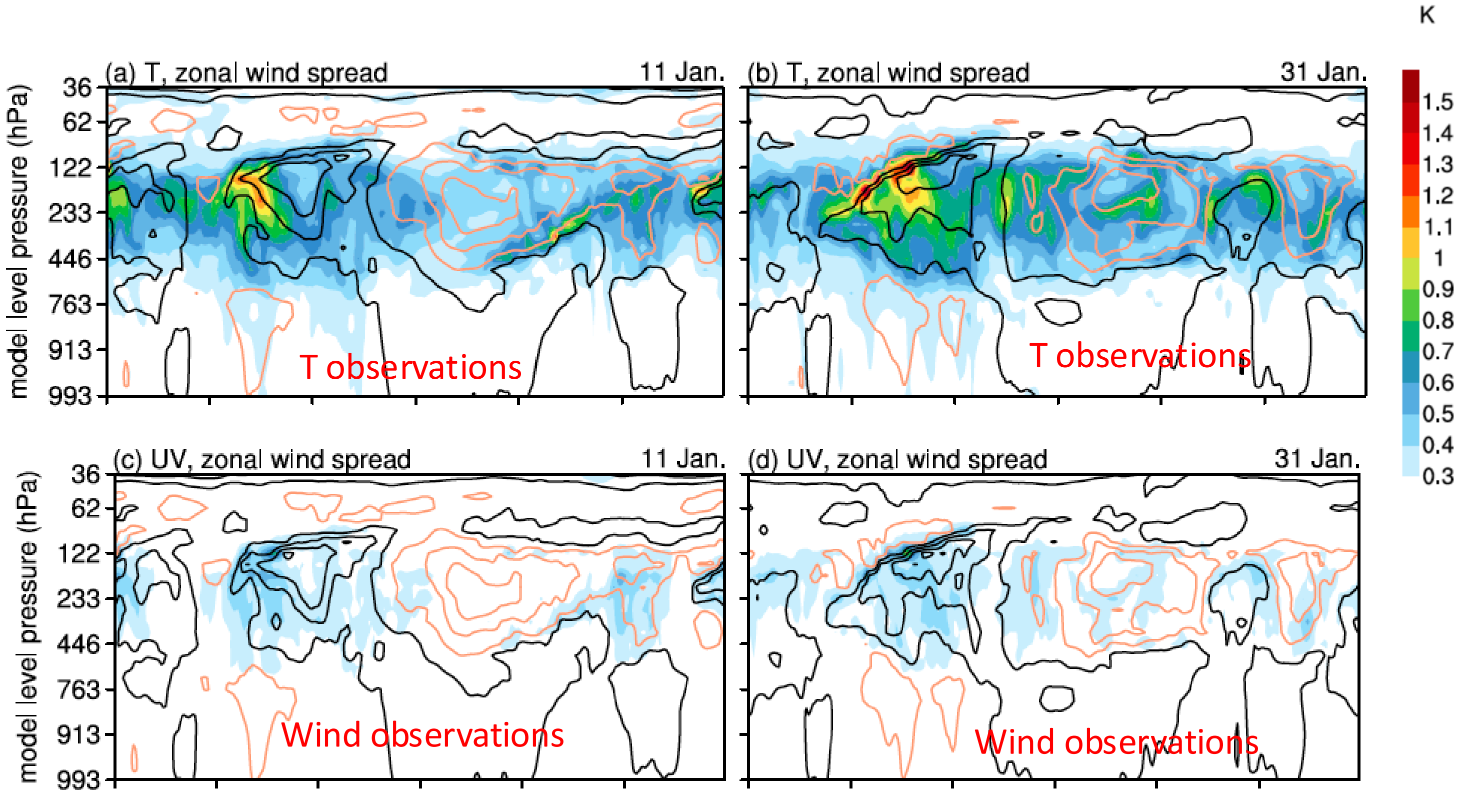
6-hour ensemble standard deviation (colours) versus flow (easterlies by black and westerlies by orange contours)

The largest short-term forecast errors are found in regions with strong zonal wind shear, both vertical and longitudinal.

From Li et al., 2023, QJRMS

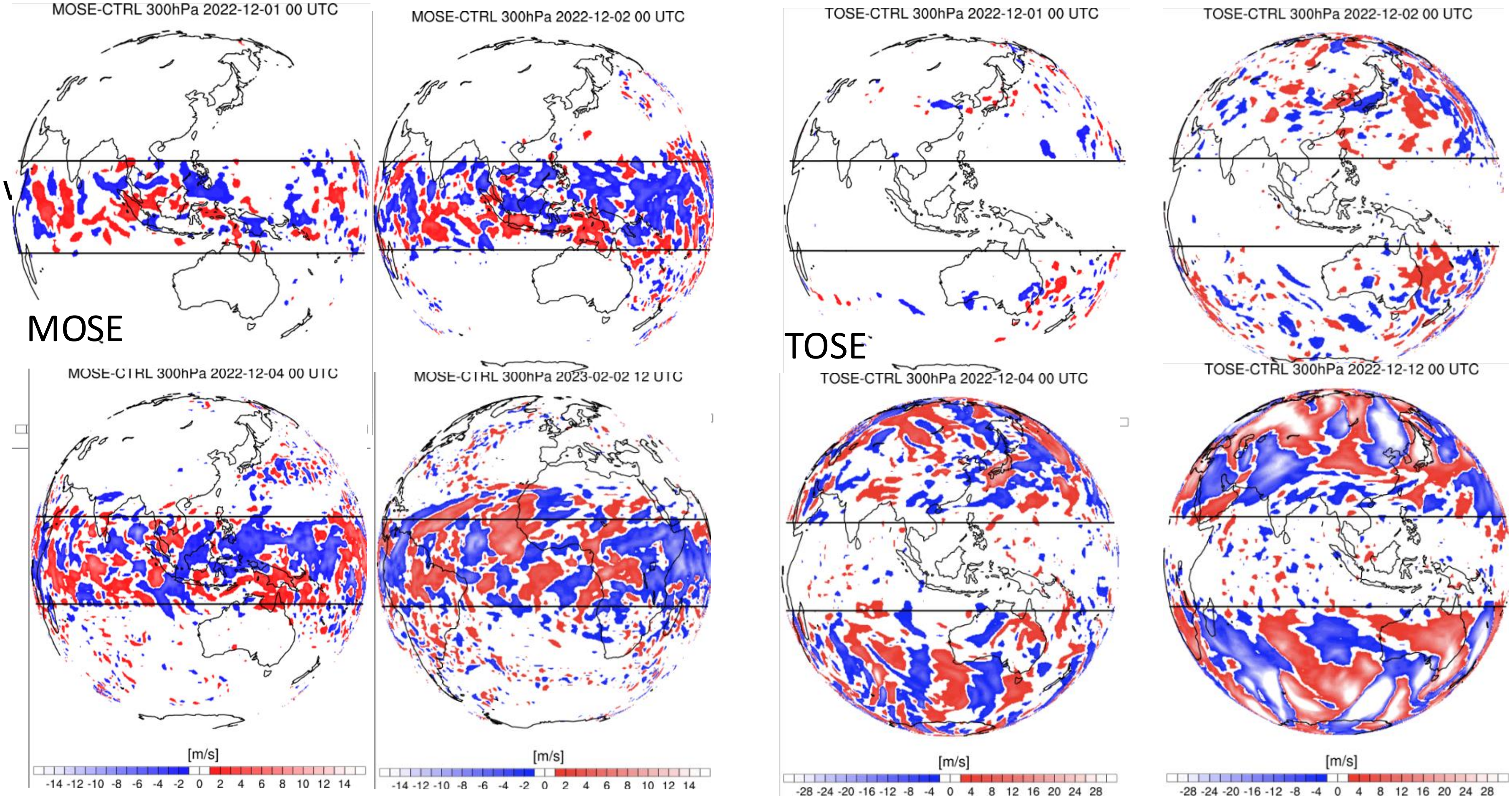
Growth of short-term forecast uncertainties

A perfect-model, EnKF study of the relative value of wind and temperature observations



From Li et al., 2023, QJRMS

How well does the GOS constrain the tropical and extratropical analyses?



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Progress in understanding tropical analysis and forecast uncertainties has been slow. Replacing nudging with tropical/extratropical observation denial OSEs (TOSE/MOSE) reveals under-observed state of the tropics.

The background wind (i.e. critical latitude) in the subtropics determines the poleward propagation of the signals from the tropical initial state. Synoptic scales are the most relevant for extratropical predictability.

On the origin of tropical analysis and forecast uncertainties

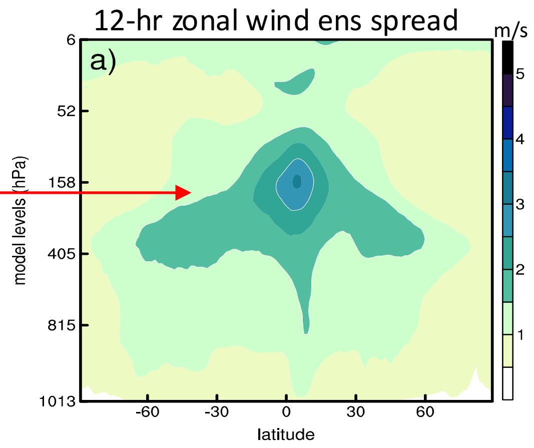
Replacing nudging with tropical/extratropical observation denial OSEs (TOSE/MOSE) reveals under-observed state of the tropics.

The wind observations are needed to constrain wind shear in the tropical UTLS.

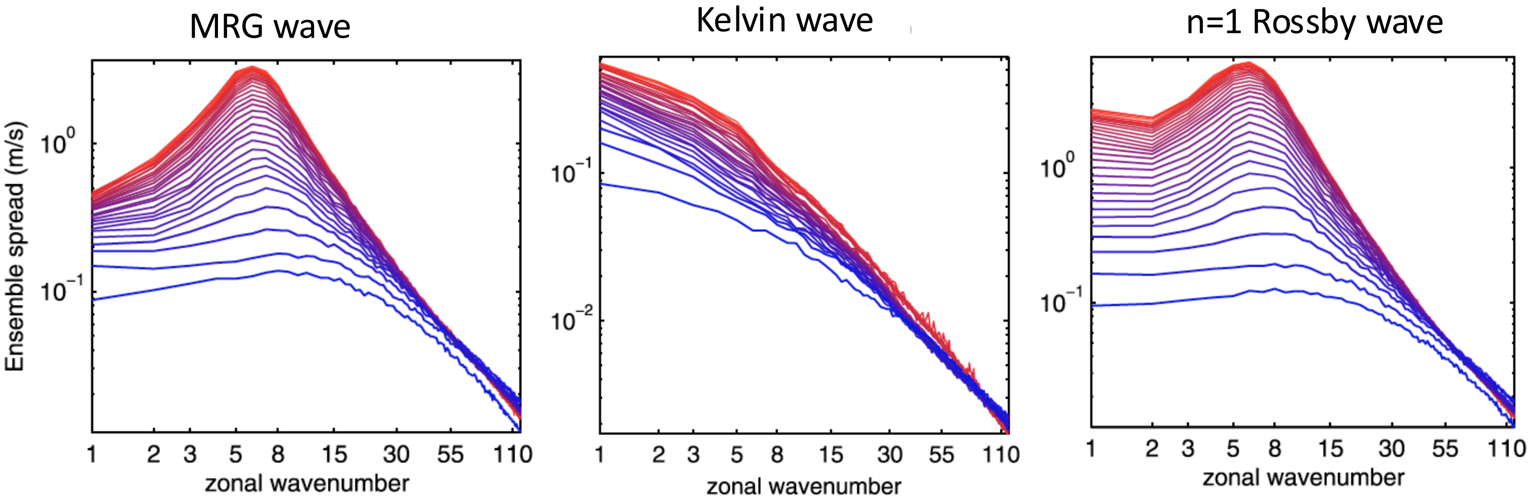
Current GOS is suboptimal, particularly in the tropics.

How about convection?

What about eqautorial waves predictability?



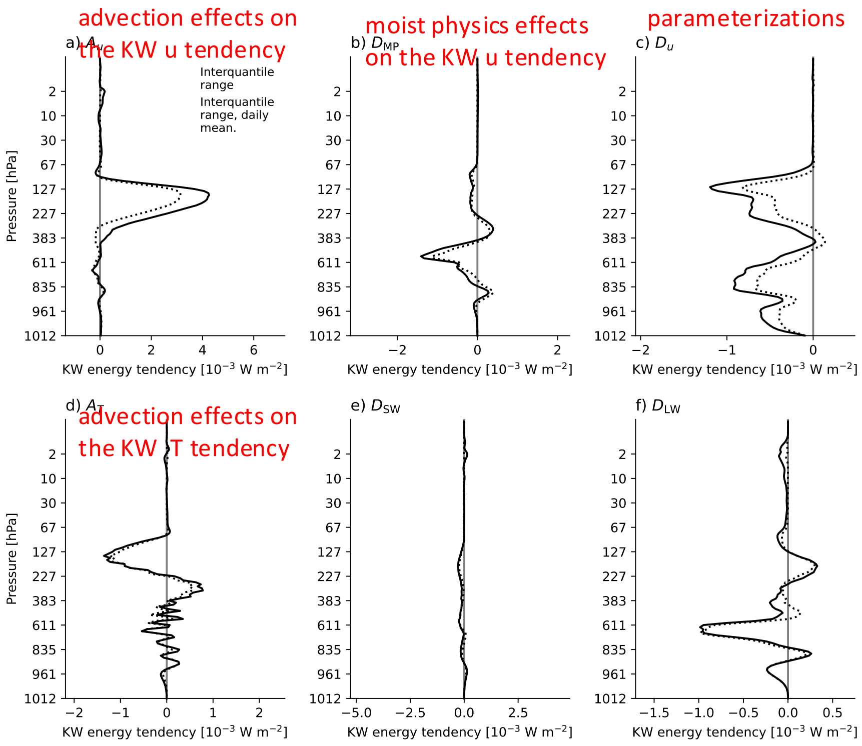
Growth of the simulated forecast errors in equatorial waves in the ECMWF ensemble



The practical predictability limit of the three main equatorial waves appears to be reached in 15-day forecasts.

From Tellus A, 2017

What processes do cause tendencies in equatorial waves? Example of the Kelvin wave



Contributions to the Kelvin wave (KW) energy tendencies due to various processes. Data are ERA5.

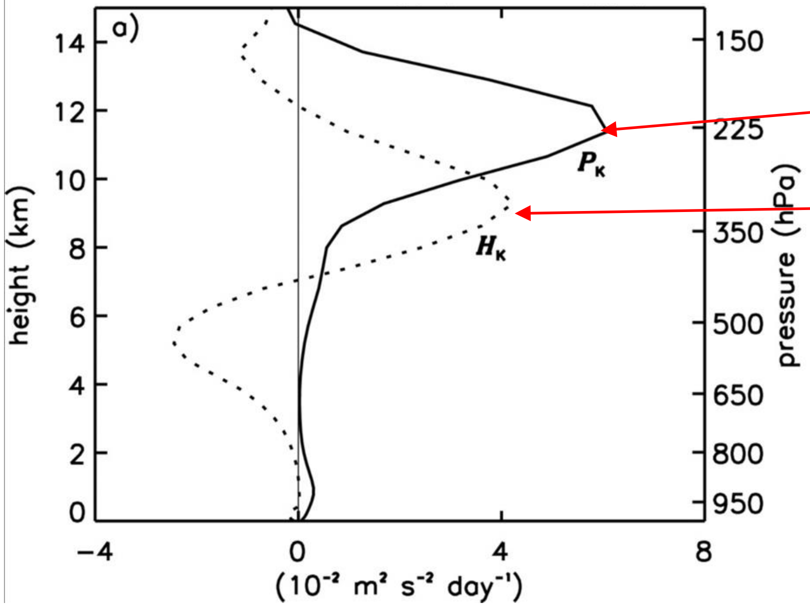
The largest tendencies, at the level with the strongest wave signals in 100-150 hPa layer, are due to advection.

Nonlinear dynamics, which causes the largest KW tendencies, may also be the main source of KW uncertainties in the UTLS.

PhD research of Katharina Holube
To be submitted soon

What processes do cause tendencies in equatorial waves? Example of the Kelvin wave

Idealised aqua-planet simulations



from Tulich and Kiladis, 2021, JAMES

Contributions to the Kelvin wave (KW) energy tendencies due to various processes. Data are ERA5.

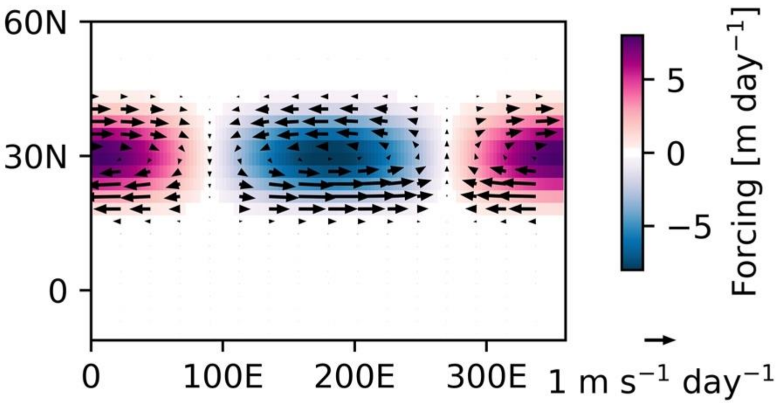
P - "remote eddy source" of the Kelvin wave kinetic energy

H - "local source" of the Kelvin wave potential energy due to tropical heating

Nonlinear dynamics, which causes the largest KW tendencies, may also be the main source of KW uncertainties in the UTLS.

Resonant excitation of Kelvin waves by interactions of subtropical Rossby waves and the zonal mean flow

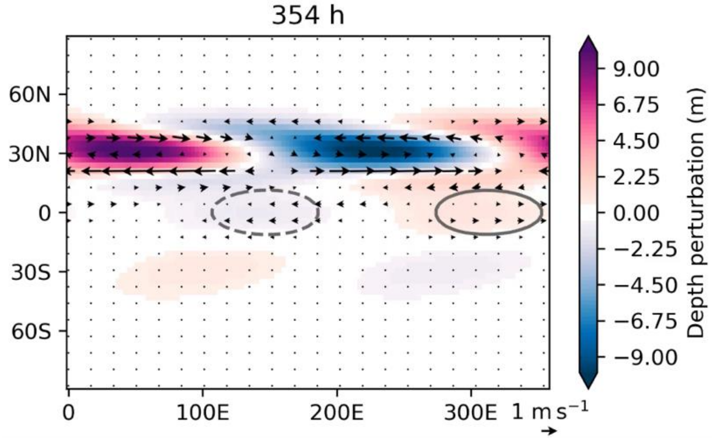
n=1 Rossby wave forcing superimposed on the steady subtropical balanced jet



$$q_{n,R} = \alpha_n e^{-i\omega_0 t}$$

Forcing frequency matches that of the Kelvin wave modified by the background flow

Kelvin wave, not present in the initial state, is excited.



Comparison of different terms involved in interactions show that the growth is mainly due to Rossby wave-mean flow interactions.

From Holube et al., 2024, JAS

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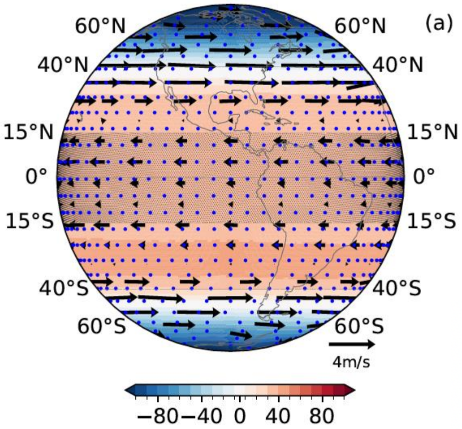
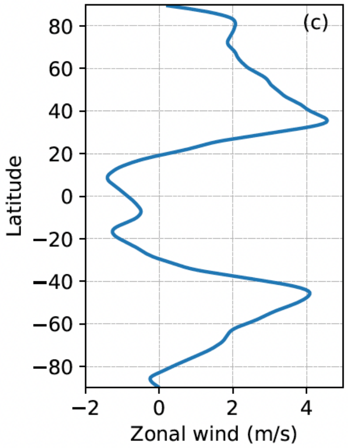
Progress in understanding tropical analysis and forecast uncertainties has been slow. Replacing nudging with tropical/extratropical observation denial OSEs (TOSE/MOSE) reveals under-observed state of the tropics.

What tropical scales and flows are more relevant for the extratropical predictability? The background wind (i.e. critical latitude) in the subtropics determines the poleward propagation of the signals from the tropical initial state. Synoptic scales are the most relevant for extratropical predictability.

Effects of the tropical initial state on extratropical predictability



TOSSE - Tropical Observing System (Simulation) Experiment: observation denial DA experiments assimilating only observations of the tropics. It offers understanding of the effects tropical initial state on extratropics.



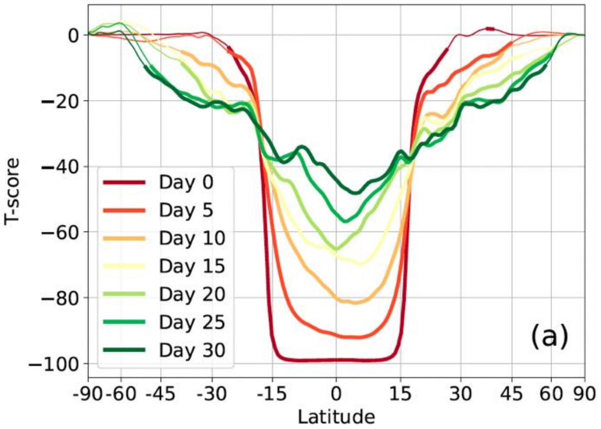
Simulated climatological state with TIGAR: tropical easterlies and westerly subtropical jets (asymmetric)

Scale-dependent evaluation of 3D-Var analyses assimilating observations within 15^0N-15^0S and forecasts focuses on Rossby waves only.

From Wang et al., 2025 Submitted to MWR, under revision

Effects of the tropical initial state on extratropical predictability

forecast improvement
(minus means better)



$$\text{T-score}(k,\varphi) = \frac{\Delta\text{TMSE}(k,\varphi)}{\text{TMSE}^{C}(k,\varphi)} \times 100$$

$$\Delta\text{TMSE} = \text{TMSE}^{C} - \text{TMSE}^{T}$$

$$\text{MSE}^{x}(k,\varphi,t) = < |\hat{x}^{k}_{\text{FC}}(\varphi,t) - \hat{x}^{k}_{\text{NR}}(\varphi,t)|^{2} >$$

From Wang et al. 2025
Submitted to MWR, under revision

Effects of the tropical initial state on extratropical predictability

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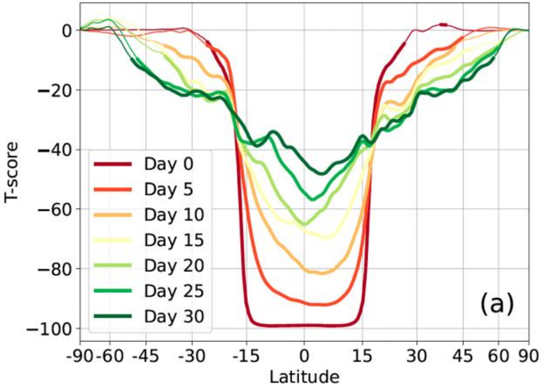
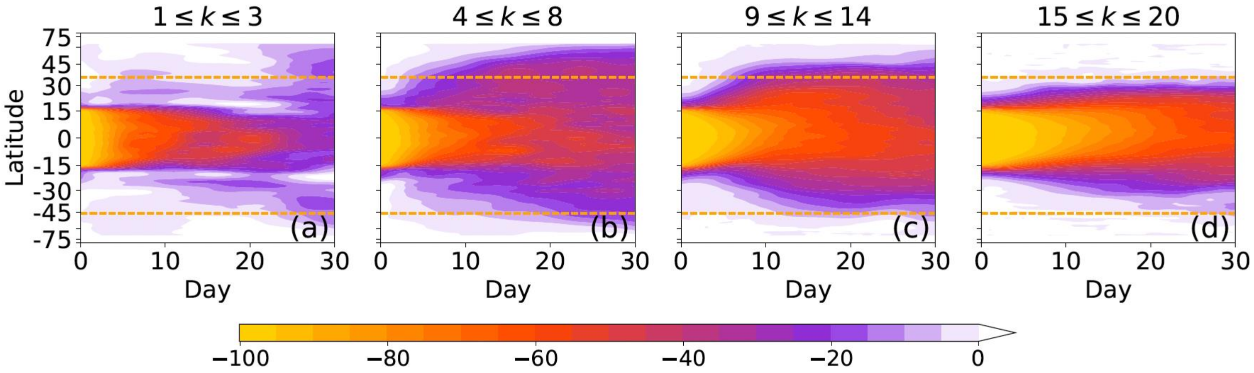


$$\text{T-score}(k,\varphi) = \frac{\Delta\text{TMSE}(k,\varphi)}{\text{TMSE}^{C}(k,\varphi)} \times 100$$

$$\Delta\text{TMSE} = \text{TMSE}^{C} - \text{TMSE}^{T}$$

From Wang et al. 2025
Submitted to MWR, under revision

Synoptic-scale initial state is most important for the accuracy of extratropical forecasts



- Effects can be understood using the theory of Rossby wave propagation on the sphere and barotropically unstable modes.
- Implications for global impacts of high-resolution tropical data assimilation and modelling: upscale effects from convective scales must outweigh the downscale influence of large-scale initial uncertainties and model errors.

Main Points

Understanding practical predictability is closely linked to understanding dynamics. Tropical circulation and predictability are influenced by subtropical dynamical processes.

Progress in understanding tropical analysis and forecast uncertainties has been slow. Replacing nudging with tropical/extratropical observation denial OSEs (TOSE/MOSE) reveals under-observed state of the tropics. We need to observe wind field gradients in all three spatial directions.

The background wind (i.e., the critical latitude) in the subtropics determines the poleward propagation of signals from the tropical initial state. Synoptic scales are most relevant for extratropical predictability.

Thank you very much for your attention.