Note for Representation of the Convectively Coupled Kelvin Waves in Modern Reanalysis Products

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August 27, 2023

Content

Abstract

Aim of the study: to deepen

- Destabilization mechanisms
- Mean-state modulation of CCKWs by testing sample model.

Examining properties:

- Precipitation
- Vertical Structure
- Energetic

Using models:

- ERA5
- MERRA-2
- CFSR
- JRA-55

Analysis target

- Precipitation variability on wavenumber-frequency domain and geographic distribution.
- Though it'll underestimate the strength of precipitation of CCKWs.
- Vertical structure of temperature anomalies.
- Diabatic heating anomalies.
- The second mode EAPE of CCKWs

Strong CCKWs activity occurs in high mean-state SST, the second mode EAPE generation is higher.

Introduction

Signature of CCEWs on wavenumber-frequency domain follows dispersion relationships of the corresponding dry waves with lower equivalent depth (lower shallow water phase speed).

Features of CCKWs:

- Propagating toward east
- The only one nondispersive wave in Matsuno mode.
- Speed of KWs is constant with the same h'.
- Both temporal and spatial range is wide.

Impacts of CCKWs:

- Extreme rainfall and severe flooding event to Indonesia, South America and Africa.
- Cyclogenesis in Indian Ocean
- Onset of monsoon over South China Sea
- Interacting with MJO and ENSO.

Simulation of CCKWs in GCMs still needs to be improved. Needing deeper understanding the modulation mechanics of CCKWs from environment variables.

Basic state of CCKW-active regions characterized with higher SST, but the mechanics of SST heating dry KWs is still unclear.

Nowadays, theoretical models of CCKWs instability mechanisms can be divided into 2 groups, using the first and the second baroclinic mode as the essential component. Both of the groups are hypothesized to grow through the generation of EAPE, 1st and 2nd vertical mode obtain different EAPE generation. EAPE diagnosis will be useful for testing the simple models of CCKWs.

Data and methods

- Reanalysis and observational data
  Reanalysis datasets:
  ERA5, MERA-2, CFSR, JRA-55 Using variables:

variables	usage
precipitation	characterizing convective activity
horizontal wind	horizontal structure
vertical pressure velocity, temperature geopotential, specific humidity	vertical structure

  mean-state relative humidity is calculating average value among 4 models.
  pressure range: 962.5 to 125 hPa.
  Exclude land data, sea data: +15 -15

  Observational data used to anomalous reanalysis data

datasets	usage
TRMM 3B42	pewcipitation examination
radiosonce-sounding data	anomalies of vertical structure of temperature, specific humidity, geopotential and wind.
HadISST	anomalies of SST

  All of the above with period 2011-18 and horizontal resolution of $2.5° \times 2.5°$

- Space-time spectral analysis
  For precipitation space-time power spectral analysis:
  - using segment length of 96 days, overlapping of 60 days.
    Each segment yields 2 DoFs.
    Edges using 5-days Hann windowing.
  - land grids are excluded from analysis.
  - Space-time power spectrum of precipitation, conducting 15 passes of 1-2-1 running-mean filter.

- By Fourier filter, CCKWs is within 2.5-20 days, zonal wavenumbers 1-14, equivalent depth 8-90 m.

Also the same in cross-spectra of temperature and diabatic heating.

- Empirical vertical mode decomposition
  CCKWs' composite vertical structure is constructed by regressing data of atmospheric variables (later will base on SST from HadISST).
  Excluding CFSR, the other three models will use HadISST as the SST analysis method. CFSR will use SST itself, since the deviation between the two is about $0.05°C$.
  In this paper, the vertical structure of 1st and 2nd baroclinic mode will be decomposed with an empirical orthogonal function (EOF) analysis.
  In math, it can be written in:

$$Q(x, y, p, t) = \Sigma_{i=1}^{N} EOF_i^Q(p) \times \hat{Q}_i(x, y, t)$$

  in which EOF is a Nth matrix to compute EOF ana., Qi is the principal component (PA) of the heating profile.
  EOF1 is similar to the structure of the 1st baroclinic structure.
  EOF2 is similar to the structure of the 2nd baroclinic structure.
  The 1st baroclinic mode is associated with deep convective clouds, and the 2nd baroclinic mode is related to stratiform clouds.
  These two leading terms capture most of the total variance of diabatic heating, which means that:

$$Q(x, y, p, t) = \Sigma_{i=1}^{2} EOF_i^Q(p) \times \hat{Q}_i(x, y, t)$$

  In this paper, the vertical structure of temp. is regarded the same as which of Q. In this assumption, EOF ana. of temperature can be approximated as:

$$T(x, y, p, t) \approx \Sigma_{i=1}^{N} EOF_i^Q(p) \times \hat{T}_i(x, y, t)$$

- Quantifying EAPE growth rate in the physical domain
  EAPE in this study is defined there as daily temporal anomalies.
  Usually used to investigate the energetic budget of CCEWs.
  Describing the difference between total eddy potential energy and the minimum total eddy potential energy, it;s formulated as:

$$E = \int_0^{p_s} \frac{1}{2} \frac{\bar{T}^2}{(\Gamma_d - \bar{\Gamma})\bar{\bar{T}}} dp$$

$\bar{\bar{T}}$ represents the daily mean temperature profile w/o remove seasonal. By EAPE budget equation, generation is from diabatic heating, conservation from mean-state APE and conservation to eddy kinetic energy. Diabatic heat source is the dominant source of EAPE generation in CCEWs if the analytical solution of simple models are a manifestation of the observed CCKWs.

Generation of EAPE form diabatic:

$$G = \int_0^{p_s} \frac{\bar{QT}}{(\Gamma_d - \bar{\Gamma})\bar{\bar{T}}} dp$$

To normalized G by EAPE:

$$\sigma = \frac{G}{E}$$

Since the EAPE generation and G is different in different vertical mode, then can be use sub-notation to represent different mode:

$$\sigma_i = 2\frac{\overline{\hat{Q}'_i \hat{T}'_i}}{\bar{\hat{T}}_i'^2}$$

$\hat{Q}'_i$, $\hat{T}'_i$ represent the CCKW-filtered PCs.
It is evident that the EAPE generation is closely relevant to precipitation variability in CCKWs band, which means that the EAPE generation is helpful to understanding precipitation anomaly.

- Quantifying EAPE growth rate in the wavenumber-frequency domain Doing Fourier transform, the growth rate can be written in:

$$\sigma_i = 2 \times \frac{real(< QT >_i^{f,k})}{< TT >_i^{f,k}}$$

This will only remain in-phase and out-phase signal, the phase can be written as:

$$\varphi_i = tan^{-1}(\frac{imag(< QT >_i^{f,k})}{real(< QT >_i^{f,k})})$$

Coherence square of phase relations:

$$Coh_i^2 = \frac{real(< QT >_i^{f,k})^2 + imag(< QT >_i^{f,k})^2}{< TT >_i^{f,k} < QQ >_i^{f,k}}$$

This study will focus on EAPE growth rate where Coh2>0.03.

Results

- CCKW precipitation
  This section is used to examine if precipitation a proxy for convection. For wavenumber-frequency domain, Fig. 2. show the signal strength greater than 1.4 (F-test statically peak of 95significant)
  Since, in the figure, all peaks are located in the CCKW band in power spectrum, this shows that CCKWs grow their amplitude against frictional process and damping processes. Also by FIG. 2., it is obvious that the three models, except CFSR, show their statically significant peaks about $h' = 25m$.
  And the signal of CFSR is underestimated.
  Also, in physical domain, since CCKWs show their peaks of precipitation variables at location of warm body water pool. And via FIG. 3., it is evident that the warm pools of SST are collocated with peaks of precipitaiton variables.

- EPAE growth rate in the wavenumber-frequency domain
  Supposing that the maintenance of CCKWs can be explained by EAPE, then by examining the growth rate of EAPE can realizs the factor that triggered the intial of CCKWs. By FIG. 4., in ERA5, NERRA-2 and CFSR, show that there is more positive EAPE growth rate overlapping with CCWKs band, which means that the enhances CCKWs signal in three models are more likely to associate with 2nd baroclinic mode.
  And also, for the three modes, the 1st baroclinic mode shows the property of damping.
  The FIG also shows the importance of the second baroclinic dynamics in destabilization in gravity waves, but not for rotating waves.
  These two wave types can be distinguished in tilting vertical structure and can be hypothesized with different instability mechanisms governed the two types of waves.
  Stronger EPAE generation can lead to stronger CCKWs precipitation.

- EAPE growth rate in the physical domain
  If FIG.5., 6., they show the same charateristics mentioned in subsection above, which associated baroclinic modes and EAPE growth rate.
  Based on the research above, it is evident that the second baroclinic mode EAPE growth rate is associated with strong CCKWs precipitation.

- Mean-state SST and the second mode CCKW EAPE growth rate
  In FIG. 8., it shows that the warm pool of SST is collocated with the positive second mode EAPE growth rate.
  This shows that the SST difference has strong impact on the second mode EAPE growth rate.
  This result in that CCKWs are strong over the area that has strong mean-state SST.
  When the SST is greater than $28°C$, EAPE growth rate in the second baroclinic mode is evident to grow as SST increasing.
  Decomposing expression of σ_2 into:

  $$\sigma_2 = 2\frac{cor(\hat{Q}_2', \hat{T}_2')std(\hat{Q}_2')}{std(\hat{T}_2')}$$

  In FIG. 10., it shows that

  - diabetic heat and temperature is more correlated under high SST.
  - diabetic heating change more severely than temperature in high SST.

  Zonal wind anomalies is in-phase with geopotential, fitting the dry KW theory.

Summary and conclusion

- CCKWs is destablized with the second baroclinic mode.
- Since it is found out that EAPE growth rate is increasing as mean-state SST. Therefore, EAPE growth rate will change as the mean-state SST, and thus modulate CCKWs.
- Though the precipitation variables can represent the CCKWs amplitude, but it is often underestimated.

In reanalysis model, it is found in this paper that the second baroclinic mode (stratiform clouds and related thermodynamics) are the key point of CCKWs maintenance.
Also, the main destabilized process of CCKWs is mainly within second vertical mode and correspond to mean-state SST.

mechanism that the second mode affect CCKWs:

- assume that a temperature perturbation with second mode form.
- low-level cold anomalies reduce CIN, triggered deep convection.
- deep convection moisten the column.
- moisture anomalies move as wave propagate toward east.
- moisture anomalies doing stratiform heating and cause amplified.

This will cause temperature anomalies more series, and thus a positive feedback loop, but this loop will exist only when the SST high enough.
If the SST is weaker, the effect which moisten will be weaker and take longer time in mid-troposphere, this will cause stratiform doesn't overlap with the heating and therefore not be amplified.
Other than convective-wave feedback, the CCKWs may also be triggered by eddy kinetic energy in mid-troposphere.