Dynamics of the Extratropical Response to Tropical Heating

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Introduction: Tropical Heating: El Niño

- **El Niño**: warming of the sea surface waters in the tropical Pacific over a time period
- **Bjerknes (1960s)**: two coupled oscillations: El Niño/La Niña (ocean) and Southern Oscillation (atmosphere) → **ENSO**
- **ENSO**: Natural climate variability influencing atmospheric patterns all over the globe
- **Droughts, floods (epidemics, e.g. Malaria)**

*Figure*: Normal Pacific pattern (left), El Niño conditions (middle), and La Niña conditions (right); source: Wikipedia
Introduction: Responses in the Extratropics: Teleconnections

- Teleconnections: correlation patterns of large-scale atmospheric circulations; precipitation and temperature relationships

Formation

- Anomalous sea surface temperature (SST) leads to anomalies in convection and large scale overturning in the atmosphere
- Resulting in strong upper tropospheric divergence in tropics and convergence in the subtropics → source for Rossby waves
- Dispersion of Rossby waves → Teleconnections

- At least 13 distinct teleconnection patterns in northern hemisphere extratropics, only some arise from SST variability
Walker and Bliss (1932), van Loon and Rogers (1978): North Pacific (NP) oscillation and North Atlantic Oscillation (NAO)

Wallace and Gutzler (1981):
- found teleconnection patterns, including Pacific–North American (PNA) pattern
- sea level pressure: teleconnections of opposite sign mainly between temperate and higher latitudes
- at 500 mbar: teleconnections more wavelike and regional, equivalent barotropic vertical structure

Horel and Wallace (1981): link between equatorial SST anomalies and the PNA

Extratropical atmospheric response to tropical heating subject to investigation by using models
Introduction: Teleconnections: PNA and NAO

Figure: The PNA (left) and NAO (right) teleconnection patterns, shown as one-point correlation maps of 500 hPa geopotential heights for boreal winter (DJF) over 1958 to 2005. In the left panel, the reference point is 45°N, 165°W, corresponding to the primary centre of action of the PNA pattern, given by the + sign. In the right panel, the NAO pattern is illustrated based on a reference point of 65°N, 30°W. Negative correlation coefficients are dashed, and the contour increment is 0.2. Adapted from Hurrell et al. (2003). Source: IPCC: Fourth Assessment Report
Hoskins, Karoly (1981)  

“The Steady Linear Response of a Spherical Atmosphere to Thermal and Orographic Forcing”  

- First modelling efforts: steady, linear response to orographic and thermal forcing → using a $\beta$–plane approximation  

\[ f = \Omega \sin \phi, \]  

$\Omega$ ... rotation rate of the Earth, $\phi$ ... latitude  

- Further papers describe use of e.g. quasi geostrophic models, primitive equation models, and General Circulation Models (GCMs)
Basic ideas:

- In tropical regions: anomalously warm ocean may lead to additional convective heating in atmosphere.
- Balanced by extra upward motion, furthermore divergence and forcing of anticyclonic vorticity at upper levels.

→ **Simplest model of tropical thermal anomaly:**

forcing anticyclonic vorticity in nondivergent barotropic model, which is linearized about a zonal flow.

- Case in this paper: barotropic model of Northern Hemisphere 300 mbar winter flow with negative vorticity source between equator and 30°N.
Barotropic models not useful for modelling thermal sources in midlatitudes because of baroclinic nature of local response to thermal forcing.

Linearized barotropic model great simplification → use of **baroclinic model**

**Thermal forcing**: placed in subtropics and in mid-latitudes

**Results:**

- Equivalent barotropic structure away from the forcing regions.
- Largest amplitudes in upper troposphere, consistent with other observational studies.
- Wavetrains in upper troposphere of baroclinic model and in barotropic model: qualitatively and quantitatively very similar.
Conclusions:

- Linear, steady-state assumption quite good approximation
- Pattern of perturbations induced by large-scale forcing are reproduced
- Results show importance for middle latitudes of subtropical forcing in the westerly wind region
"Steady Response to Tropical Heating in Barotropic and Baroclinic Models"

Overview

- Response to stationary waves is barotropic in the extratropics, even though the atmosphere having vertical shears is baroclinic → because stationary waves dominated by height independent component.

- To study extratropical responses to fixed tropical heat source: one-level barotropic model consisting of single vorticity equation widely used.

- Tropical heat source: such as one associated with tropical SST anomalies during El Niño, appears as tropical divergence forcing in barotropic model.
Assumption:

- deep tropical heating is mainly balanced by adiabatic cooling in Tropics
- resulting stretching due to ascending motion acts as vorticity source in barotropic vorticity equation
- Baroclinic model with tropical heating and barotropic model with divergence forcing only should yield same extratropical wave train
Ting (1996)  Aims and Method

- **Uncertainty**: which vertical level good choice for applying the barotropic model?
- **Tropical heat source**: imposed on linear baroclinic model (heating) and on one–level barotropic model (divergence)
- **Focus**: determine an equivalent barotropic level using a high vertical resolution model
  
  -> Comparison of responses of the two model
  
  -> Examination of the sensitivities of barotropic model response to the choice of zonal mean states at different vertical levels
Stationary barotropic model consists of vorticity equation:

\[ 0 = -\nabla \cdot (f + \zeta)V - \nu \nabla^4 \zeta - \epsilon \zeta, \]

\( f \) ... Coriolis parameter, \( \zeta \) ... vorticity, \( V \) ... horizontal wind vector, \( \nu \) ... biharmonic diffusion coefficient, \( \epsilon \) ... Rayleigh friction

Application of barotropic model on one particular level: vorticity equation is linearized about zonal mean state at that level
Steady linear baroclinic model: global spectral model using 20 sigma (σ) levels

Basic equations: equations for vorticity, divergence, temperature, logarithmic surface pressure, geopotential height, σ-coordinate vertical velocity (linearized about a zonal mean basic state)

Tropical diabatic heating $\dot{Q}$ centered on the equator and the dateline:

$$\dot{Q} = V(\sigma)H(\lambda, \phi),$$

$V$, $H$ . . . vertical and horizontal heating distributions
$\lambda$, $\phi$ . . . longitudes and latitudes

Production of rotational and divergent responses
Figure: Horizontal (a) and vertical (b) distributions of the tropical heat source used in the linear baroclinic model. Contour interval in (a) is 0.5°K.
Streamfunction response:

- Figure: Longitudinal–vertical cross sections on streamfunction responses of the linear baroclinic model at 15°N (a), 30°N (b), 45°N (c), and 75°N (d). Contour interval is 10 $m^2/s$, negative values are dashed.
- Vertical structure becomes more barotropic in poleward direction
- Transition from baroclinic mode to the equivalent barotropic structure is at 30°N (Subtropics)
Response of the divergence:

- Figure: Longitudinal–vertical cross sections of divergence responses of the linear baroclinic model at equator.
- Vertical structure of the response of divergence shows similarities at different latitudes (at the equator, at 15°N, and at 30°N)
- Always: distinct divergence (upper-level center) and convergence (lower-level center) with opposite sign
Linear barotropic model useful in interpreting observational and GCM results in tropical–extratropical interaction problems

But: strong sensitivities to levels of basic state the equations are linearized about

Good agreement of barotropic and baroclinic model responses

Barotropic model linearized about 350mbar basic state yields extratropical wave train similar to baroclinic solution → equivalent barotropic level at 350mbar-level
Lin, Derome, Brunet (2007)

"The Nonlinear Transient Atmospheric Response to Tropical Forcing"

- Primitive-equation dry atmospheric model: investigate the atmospheric transient response to tropical forcing
- Tropical thermal forcing: added to temperature equation and kept constant during the run
- Two main focuses:
  1. tropical signal followed by the extratropical response
  2. nonlinearity of the response as function of amplitude of tropical forcing (ENSO)
Response in Pacific–North American region: well developed within one week

Response pattern resembles the PNA

Response in North Atlantic area: established within two weeks

Main contribution to asymmetric response distribution and phase difference comes from Tropics

Tropical and extratropical response interact with mean zonal flow, leading to change in Rossby wave propagation
Lin, Derome, Brunet (2007)

Results:

- Feedback from synoptic-scale eddies: makes positive contribution for response in extratropics → supports generation and maintainance of nonlinear response

- Advantages of simple model:
  - large ensemble of model runs can be integrated
  - interpretation of the results easier because of idealized forcing and no detailed physical processes

- Large ensemble size (350 runs) provide robust result concerning asymmetric responses of El Niño and La Niña
“Dynamics of the Extratropical Response to a Tropical Atlantic SST Anomaly”

- Experiments with atmospheric general circulation models (AGCMs): considerable nonlinearity with respect to sign of forcing and to spatial structure of forcing
- Positive SSTA: produced south–north dipole in geopotential heights, like the NAO
- Negative SSTA: produced eastward propagating wave train, without northern lobe of the NAO
Atmospheric response: linear and nonlinear component

Possible explanations:
- **wave propagation** and **transient eddy feedback** (for the linear response)
- **thermodynamics** and **dynamics** (for the nonlinear response)

Focus of paper: examination of response to tropical Atlantic SST forcing, especially the role of transient eddy feedback in generating the NAO, and on sources of nonlinearity of the response

Used models: linear baroclinic model (for linear response), nonlinear barotropic vorticity equation model (for nonlinear response), statistical storm–track model
Extratropical responses dominated by responses to transient eddy forcing, especially the NAO response results from transient eddy forcing centered in the jet exit (subtropical jet stream).

Transient eddy feedback is sufficient to explain the linear response.

Eddy forcing in the jet exit results when a basic state is perturbed by the linear response to tropical heating.

Dynamical origin of the nonlinear component of the response: asymmetry in the response to positive and negative SST anomalies may partly result from self-advection of perturbation induced by transient eddy forcing.
THANKS FOR YOUR ATTENTION

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