wege entstehen, indem wir sie gehen
ways emerge in that we go them

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Regional and Local Climate Modeling and Analysis Research Group
ReLoClim

Dynamics of the Extratropical Response to Tropical Heating

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Second Split Workshop in Atmospheric Physics and Oceanography, 24th – 28th May

1. Introduction
   - El Niño
   - Teleconnections
2. First Attempts of Modelling the Atmospheric Response
   - Hoskins, Karoly (1981): The Steady Linear Response of a Spherical Atmosphere to Thermal and Orographic Forcing
3. Determining the Response to Tropical Forcing
   - Ting (1996): Steady Response to Tropical Heating in Barotropic and Baroclinic Models
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   - Li, Robinson, Hoerling, Weickmann (2007): Dynamics of the Extratropical Response to a Tropical Atlantic SST Anomaly

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: **E**l **N**iño/La Niña (ocean) and **S**outhern **O**scillation (atmosphere) → **ENSO**
- ENSO: Natural climate variability influencing atmospheric patterns all over the globe
- Droughts, floods (epidemics, e.g. Malaria)

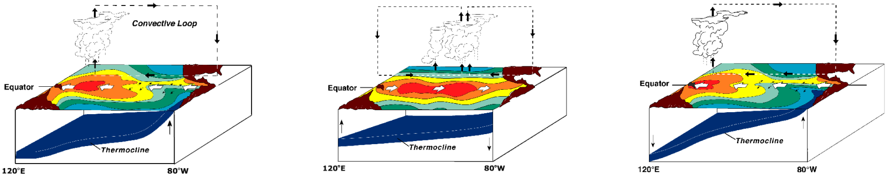


Figure: Normal Pacific pattern (left), El Niño conditions (middle), and La Niña conditions (right); source: Wikipedia

- 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 troposheric 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

Introduction: *Teleconnections: History*

- 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*

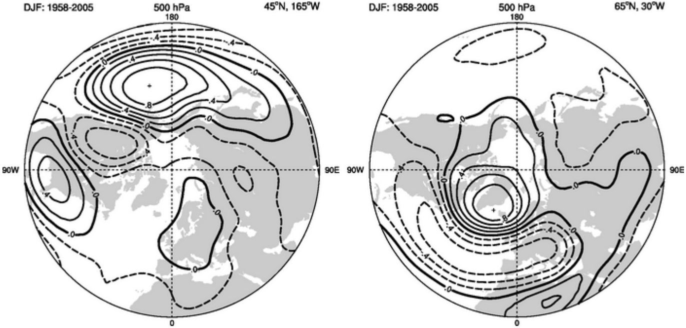


Figure: The PNA (left) and NAO (right) teleconnection patterns, shown as one-point correlation maps of 500 hPa geopotential heights for boreal winter (DJF) over 1958 to 2005. In the left panel, the reference point is 45°N, 165°W, corresponding to the primary centre of action of the PNA pattern, given 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 β*–plane approximation*

β–plane approximation

- Coriolis parameter f is set to vary linearly in space, important for Rossby waves:

$$f = \Omega \sin \phi,$$

Ω . . . rotation rate of the Earth, ϕ . . . latitude

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

Hoskins, Karoly (1981)

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

Hoskins, Karoly (1981)

- 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 troposhere, consistent with other observational studies
- Wavetrains in upper troposphere of baroclinic model and in barotropic model: qualitatively and quantitatively very similar

Hoskins, Karoly (1981)

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

Ting (1996)

“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 waes 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

Ting (1996)

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

Ting (1996) *Model description: Barotropic model*

- Stationary barotropic model consists of **vorticity equation**:

$$0 = -\boldsymbol{\nabla} \cdot (f + \zeta)\mathbf{V} - v\nabla^4\zeta - \epsilon\zeta, \qquad (1)$$

f . . . Coriolis parameter, ζ . . . vorticity, **V** . . . horizontal wind vector, v . . . biharmonic diffusion coefficient, ϵ . . . Rayleigh friction

- Application of barotropic model on one particular level: vorticity equation is linearized about zonal mean state at that level

Ting (1996) *Model description: Baroclinic model*

- 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:

  $$\dot{Q} = V(\sigma)H(\lambda, \phi), \tag{2}$$

  V, H . . . vertical and horizontal heating distributions
  λ, ϕ . . . longitudes and latitudes
- Production of rotational and divergent responses

Ting (1996) *Equatorial heat source in winter*

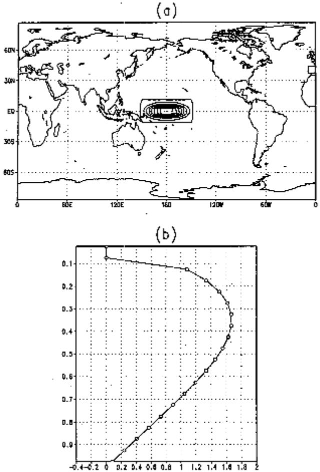
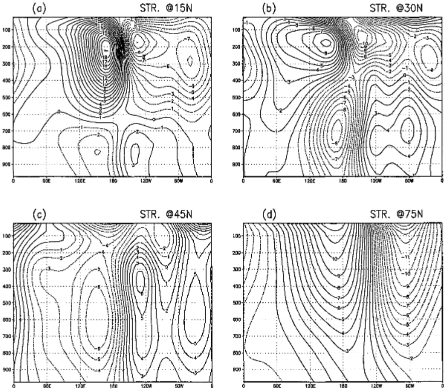


Figure: Horizontal (a) and vertical (b) distributions of the tropical heat source used in the linear baroclinic model. Contour interval in (a) is 0.5°K.

Ting (1996) *Results*

Streamfunction response:

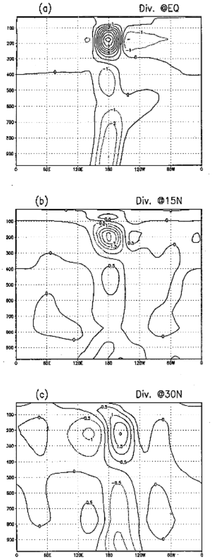
- Figure: Longitudinal–vertical cross sections on streamfunction responses of the linear baroclinic model at 15°N (a), 30°N (b), 45°N (c), and 75°N (d). Contour interval is 10 m^2/s, negative values are dashed.
- Vertical structure becomes more barotropic in poleward direction
- Transition from baroclinic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



Ting (1996) *Results*

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



Ting (1996) *Conclusions*

- Linear barotropic model useful in interpreting observational and GCM results in tropical–extratropical interaction problems
- But: strong sensitivities to levels of basic state the equatiuns 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 $\longrightarrow$ 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)

Lin, Derome, Brunet (2007) *Results:*

- 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 $\longrightarrow$ 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

Li, Robinson, Hoerling, Weickmann (2007)

“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

Li, Robinson, Hoerling, Weickmann (2007)

Basics and Aims:

- Atmospheric response: linear and nonlinear component
- Possible explainations:
  - **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

Li, Robinson, Hoerling, Weickmann (2007) *Results:*

- 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: assymetry in the response to positive and negative SST anomalies may partly result from self–advection of perturbation induced by transient eddy forcing

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THANKS FOR YOUR ATTENTION

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