Interaction of physical and dynamical processes in atmospheric teleconnections

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ECMWF System 4 forecast for DJF 2015/16

NINO3.4 SST anomaly plume
ECMWF forecast from 1 Sep 2015
Monthly mean anomalies relative to NCEP CHI 1981-2010 climatology

IC: 1 Sep 2015
ECMWF Seasonal Forecast
Mean Z500 anomaly
Forecast start reference is 01 Oct 15
Ensemble size = 51, climate size = 460
Solid contour at 1% significance level

IC: 1 Nov 2015
System 4
ECMWF Seasonal Forecast
Mean Z500 anomaly
Forecast start reference is 01 Nov 15
Ensemble size = 51, climate size = 460
Solid contour at 1% significance level

ERA Interim
Foundations: Wallace and Gutzler 1981

The Pacific / North American (PNA) pattern: correlations

Fig. 16. As in Fig. 12, but for base grid points (a) 20°N, 160°W; (b) 45°N, 165°W; (c) 35°N, 115°W; (d) 30°N, 85°W.
Correlation of 700hPa height with
a) PC1 of Eq. Pacific SST
b) SOI index

Schematic diagram of tropical-extratropical teleconnections during El Niño
Response to a tropical heat source (15N):

a) height (lon, z) at 18N
b) 300hPa vorticity
c) 300hPa height
First barotropic normal mode at four times during a half-cycle:

- East. Atlantic phase
- PNA phase
Impact of anomalous forcing on flow regime frequency

Lorenz (1963) truncated convection model with additional forcing (Molteni et al. 1993; Palmer 1993; Corti et al. 1999)

- \( \frac{dX}{dt} = \sigma (Y - X) \)
- \( \frac{dY}{dt} = -XZ + rX - (Y - Y^*) \)
- \( \frac{dZ}{dt} = XY - bZ \)
A number of dynamical processes affect teleconnections:

- Diabatic heating anomalies are not necessarily “forced” by SST anomalies
- Anomalous heating sources do not occur in isolation; signals originated from different parts of the tropics may interfere in a constructive or destructive way
- Extratropical equilibration mechanisms are relevant to both the spatial pattern and the stability (persistence) of the extra-tropical response
- Wave propagation from the tropics to the extra-tropics may be significantly affected by interactions with the stratosphere
Observational and model data

- **Observational data:**
  - ERA-Interim re-analysis, 1979-2014
  - GPCP 2.2 monthly mean precipitation, 1979-2014

- **Numerical model / simulations:**
  - ECMWF System-4 re-forecasts + operational forecasts
  - 1981-2010 + 2011-2013
  - DJF season from 1 Nov. runs (fc. months 2-4)
  - 51-member ensembles
Local correlation between SST and rainfall anomalies

a) $\text{cor (SST ERA-int, prec GPCP)}$ DJF

b) $\text{cor (SST, prec Sys4)}$ DJF
Teleconnections from Indian Ocean & West Pacific
Net heat flux at ocean surface from ERA-interim
Influence of land-sea contrast on planetary wave variability

- **Thermal equilibration of planetary waves**: Variability in the phase of planetary waves with respect to the surface temperature distribution
  - Mitchell and Derome (1983)
  - Shutts (1987)
  - Marshall and So (1990)

- **The Cold Ocean Warm Land pattern**: observations and dynamics
  - Wallace, Zhang and Bajuk (1996)
  - Molteni, King, Kucharski and Straus (2011)
A QG model of thermal equilibration

\[
\partial_t \zeta_2 = - \mathbf{v}_2 \cdot \text{grad} (\zeta_2 + f) - f D_2
\]

\[
\partial_t T_1 = - \mathbf{v}_1 \cdot \text{grad} T_1 + S \omega + c_p^{-1} H
\]

\[
\partial_t \zeta_0 \approx 0 \approx -f D_0 - k_{\text{drag}} \zeta_0
\]

\[
D_2 \approx -D_0 \approx -\omega / \Delta p
\]

\[
H = k_{\text{rad}} (\varepsilon T_s - T_1) + g \partial_p F_H
\]
a) Thermally equilibrated solution

\[ \mathbf{V}_2 \cdot \nabla (\zeta_2 + f) \approx 0, \quad -fD_2 \approx 0 \]

\[ \mathbf{V}_1 \cdot \nabla T_1 + S \omega \approx 0, \quad c_p^{-1} H \approx 0 \]

\[ fD_0 \approx 0, \quad -k_{\text{drag}} \zeta_0 \approx 0 \]

\[ U_2 = \beta / n^2 = \partial_y f / n^2 \]

\begin{align*}
\sim 300 \text{ hPa} & \quad \begin{array}{c}
L \\
\hline
H
\end{array} & - \mathbf{V}_2 \cdot \nabla (\zeta_2 + f) \approx 0, \quad -fD_2 \approx 0 \\
\sim 600 \text{ hPa} & \quad \begin{array}{c}
C \\
\hline
W
\end{array} & - \mathbf{V}_1 \cdot \nabla T_1 + S \omega \approx 0, \quad c_p^{-1} H \approx 0 \\
\sim 900 \text{ hPa} & \quad \begin{array}{c}
\hline
\uparrow
\end{array} & -fD_0 \approx 0, \quad -k_{\text{drag}} \zeta_0 \approx 0 \\
\text{Land} & \quad \text{Sea} & \quad T_s \approx T_0 \\ & & T_s > T_0 \end{align*}
b) Thermally forced solution

\[ \nabla \cdot \mathbf{V}_2 \cdot \text{grad} (\zeta_2 + f) \approx f D_2 \]

\[ \nabla \cdot \mathbf{V}_1 \cdot \text{grad} T_1 + S \omega \approx -c_p^{-1} H \]

\[ -f D_0 \approx k_{\text{drag}} \zeta_0 \]

\[ U_2 > \beta / n^2 = \partial_y f / n^2 \]
A simple diagnostic for thermal equilibration

**Thermal balance Wave index (TW):**

Zonal wavenumber-2 component of net surface heat flux (NSHF, positive downward) in the 40-70 °N latitudinal band:

(Molteni, King, Kucharski and Straus, Clim. Dyn. 2011)

\[
TW = 0.5 \times ( \text{NSHF}_{30E-120E} + \text{NSHF}_{150W-60W} - \text{NSHF}_{120E-150W} - \text{NSHF}_{60W-30E} )
\]

TW anomalies are: positive in the forced phase (COWL pattern) negative in the equilibrated phase
The TW index and co-varying patterns in ERA-Interim

Thermally-balanced Wave index (positive in COWL phase) in DJF 1982 - 2011

Covariance with TW index in DJF:
Z 500 hPa

Net surface Heat flux
Covariances with TW index in S4

a) cov (tw, gh_500)

b) cov (tw, u_10m)

c) cov (tw, LSHu)

d) cov (tw, T_2m)
TW pattern: heat balance at 850 hPa

From an ensemble of perp. winter runs with the ICTP AGCM

U-advection

V-advection

diab. heating
TW pattern and the teleconnection from Ind.Oc. – W.Pac. in DJF
A role for the stratosphere (Fletcher, Kushner, Cassou 2010/2013/2015)

Fletcher & Kushner 2010

FIG. 5. The ensemble-mean JF zonal mean geopotential height response as a function of latitude and pressure in (a) TIP, (b) TPO, (c) TIO, and (d) the sum of the TPO and TIO responses. The contour interval is 20 m and negative contours are dashed.
Zonal mean heat transport \([v^*T^*]\) in the lower stratosphere

(h) 100hPa Heat flux response (m K s\(^{-1}\))

- TOTAL
- EM
- EM-LIN
- EM-NONLIN
- FL
- EM-LIN wv-1
- EM-LIN wv-2

[Map showing zonal mean heat transport in the lower stratosphere]
100 hPa temp. covariance with TW index
Decadal near-sfc. temperature variability: the "hiatus"

Trenberth et al 2014, Nature Climate Change

Linear trends from HadCRUT:
1984-1998: 0.26 °C/decade
1998-2012: 0.04 °C/decade

Fig. S1. For NDJFM, the global mean temperature for 1970 to 2013 and the linear trend for 1998-2013 (using NOAA data relative to the base period 1900-1999). Also shown in red are the temperature anomalies for 30-65°N relative to the mean for 1979-2013 from ERA-I data. In northern winter, when ENSO is strongest, the slight cooling trend in the 2000s exacerbates the hiatus and the coldest values are in La Niña years, however the coldest years for 30-65°N are years of negative NAO (see Figure S5).
Impact of PDO variability

Kosaka and Xie (Nature 2013)
Impact of N.Hem. extratropical variability

Saffioti et al 2015: Statistical correction of ERA-interim trends
Weighted ensemble means of S4 re-forecasts

- For each year and ensemble member, we define two weights as function of the re-forecast TW index:
  - \( W_A \): largest when the TW index of the ensemble member is close to the TW index from ERA
  - \( W_0 \): largest when the TW index of the ensemble member is close to 0

- For each year, we compute two weighted ensemble means:
  - \( \text{Ens}_A \): weighted average according to \( W_A \) weights
  - \( \text{Ens}_0 \): weighted average according to \( W_0 \) weights

- Computation of trends:
  - From 5-year or 5-winter running means (to filter out ENSO)
  - Periods: tr1 = 1984 to 1998, tr2 = 1998 to 2011
DJF variability in weighted S4 ensembles

TW index

ERA-int
Ens_mean
Ens_A
Ens_0

SST Nino3+4

Ens_A
Ens_0

T.2m
NH_land

Ens_A
Ens_0

T2 = -0.3°C/10yr

Europe (20W-40E, 30N-70N):
-0.34 °C

Ens_A - Ens_0

-0.49 °C

0.21 °C
Conclusions

• Heat fluxes at the ocean surface play an important role in teleconnections between the tropics and the extratropics. In the tropics, they determine the strength (and sign) of the relationship between SST and rainfall anomalies. In the northern extratropics, they provide a flow-dependent thermal forcing which allows for distinct configurations of quasi-stationary waves.

• The teleconnection pattern associated with rainfall variability in the tropical Indian Ocean and the Maritime Continent shows a close similarity to the pattern of planetary wave variability (COWL) associated with increased/decreased intensity of the heat fluxes over the northern oceans. This suggests that the Indian Ocean teleconnection to the North Pacific & Atlantic may result in the stabilization of one specific equilibrium for the thermal balance of planetary waves.

• The effect of anomalous Indian ocean heating on the heat transport into the NH polar vortex is consistent with the association between zonal mean wind and planetary wave phase predicted by thermal equilibration theory.

• Changes in the phase of the COWL pattern, and the associated heat flux anomalies, gave a significant contribution to the slow-down in warming trends over the northern continents during the winters of the last 15 years. Weighted ensemble means derived from the ECMWF System-4 reforecasts, which differ in terms of strong vs weak COWL variability, indicate that the change in the prevailing COWL phase accounts for a decrease in the DJF warming trend over land by ~ 0.3 deg/decade during the last 15 years.