Ocean Mixed Layer Dynamics and its Impact on Climate Variability

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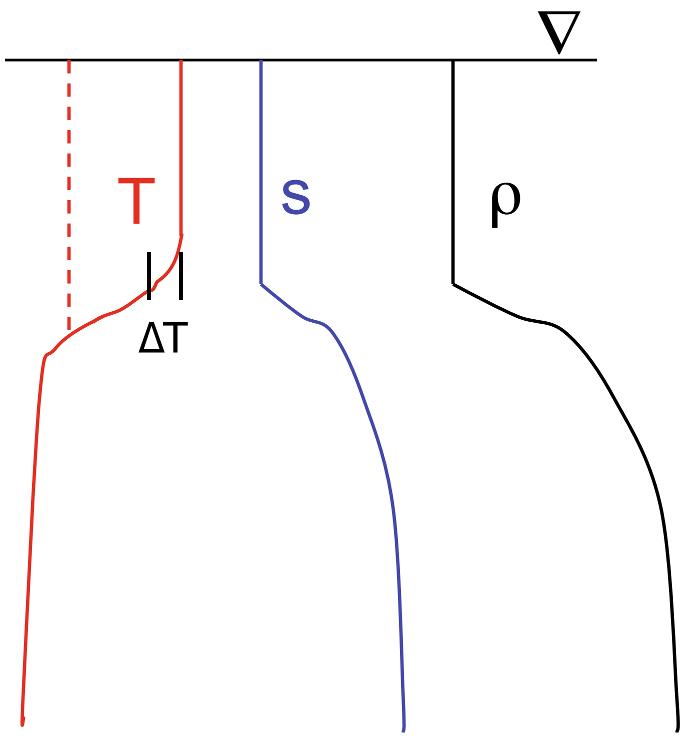
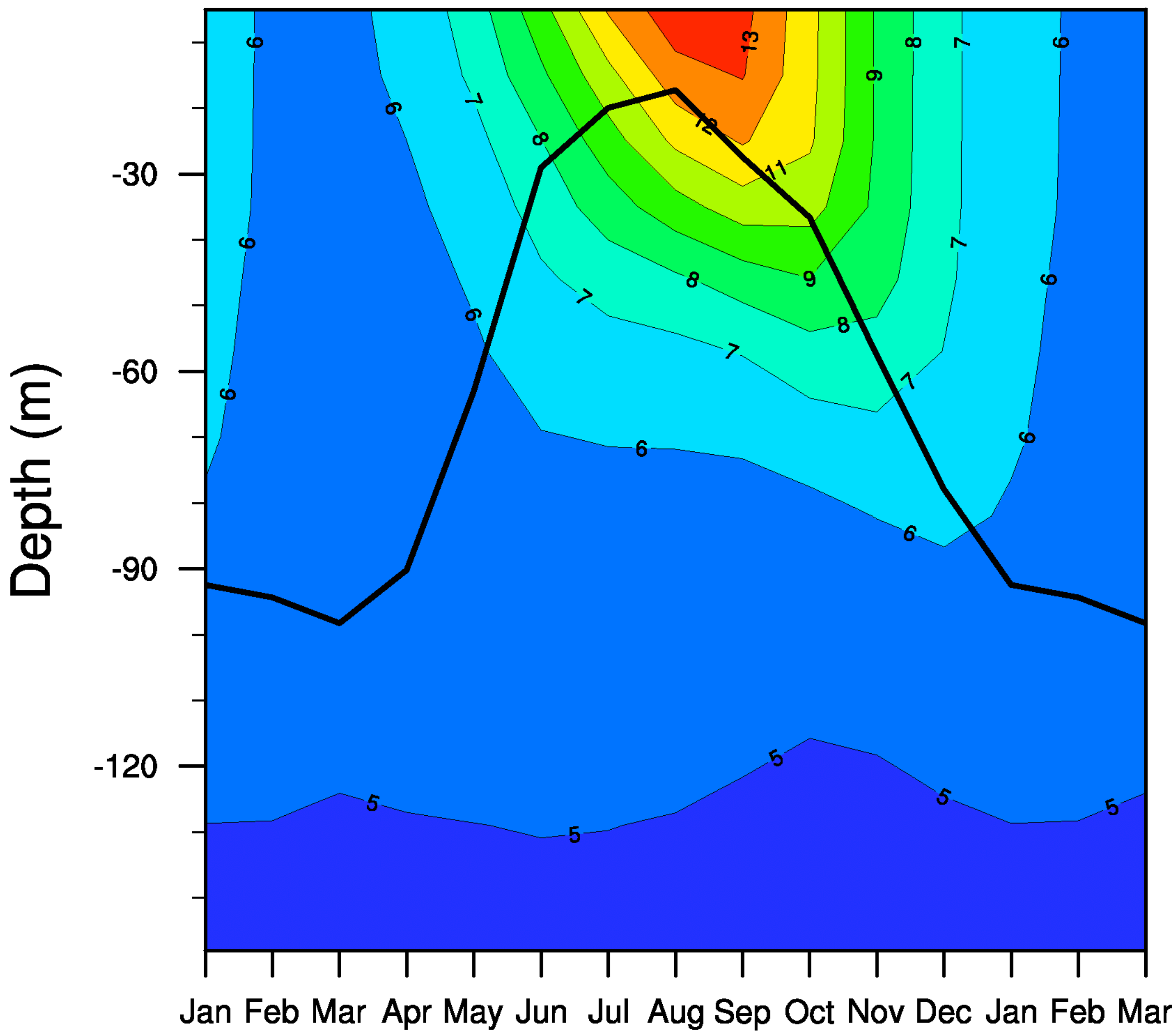
Ocean Mixed layer

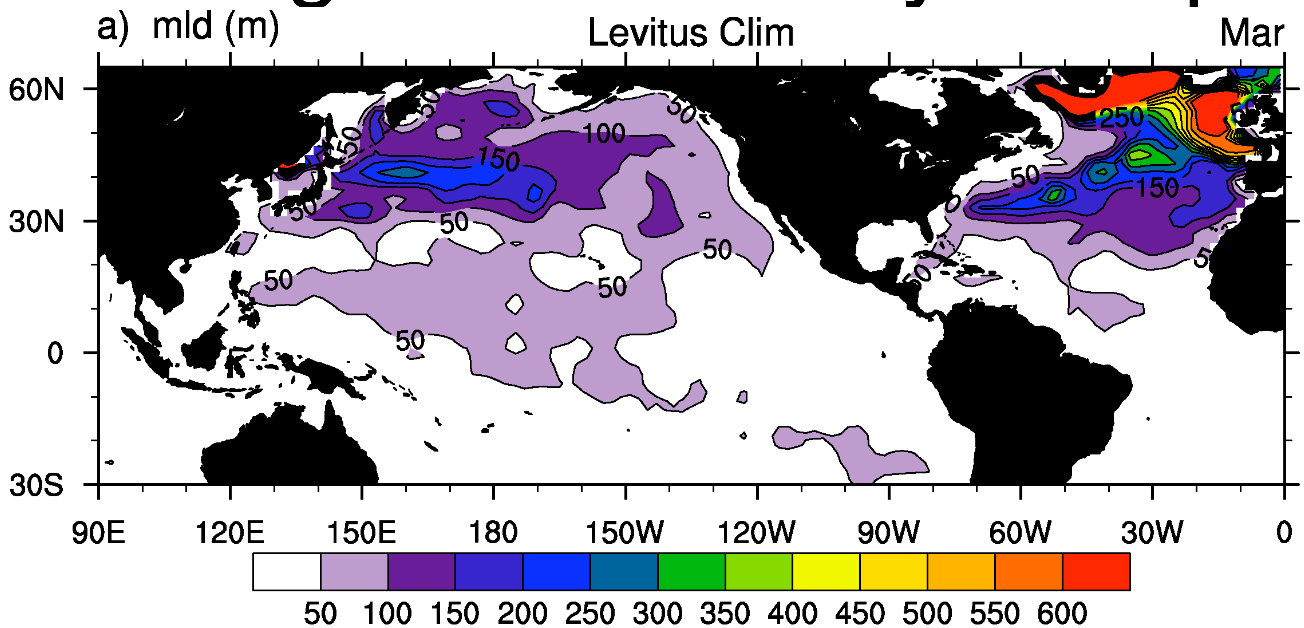
- Turbulence creates a well mixed surface layer where temperature (T), salinity (S) and density (ρ) are nearly uniform with depth
- Primarily driven by vertical processes (assumed here) but can interact with 3-D circulation
- Density jump usually controlled by temperature but sometimes by salinity (especially in high latitudes)
- Often " measured" by the depth at which T is some value less than SST (e.g. ΔT = 0.5)
- Under goes large seasonal cycle
- This impacts the evolution of ocean temperature anomalies and has important biological consequences

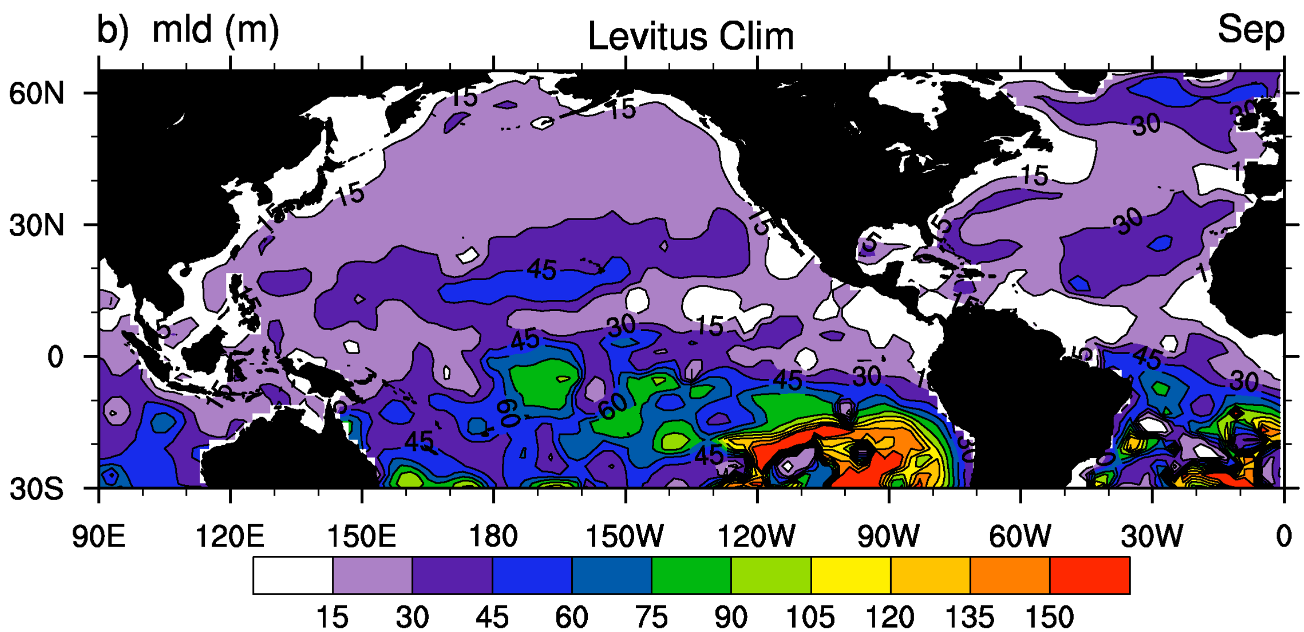


Seasonal Cycle of Temp & MLD the Northeast Pacific (50ºN, 145ºW)



Climatological Mixed Layer Depth (m)





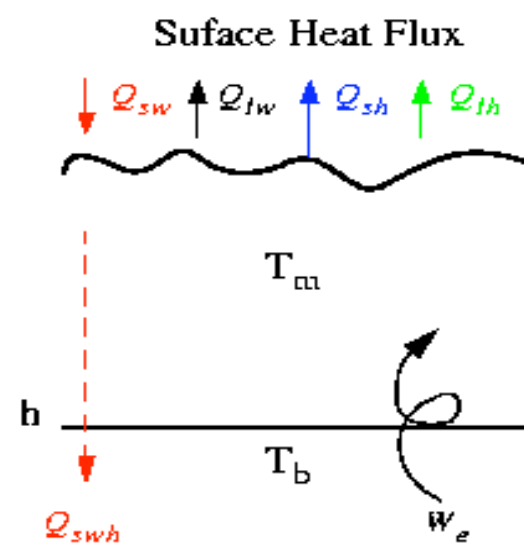
SST Tendency Equation

Integrated heat budget over the mixed layer:

$$\frac{\partial T_m}{\partial t} = -\vec{v} \cdot \nabla T_m + \left(\frac{w + w_e}{h} \right) (T_b - T_m) + \frac{Q_{net} + Q_{swh}}{\rho c h} + A \nabla^2 T_m$$

Variables

v	-	velocity (current in ML)
T_m	–	mixed layer temp (SST)
T_b	–	temp just beneath ML
h	–	mixed layer depth
w	–	mean vertical velocity
w_e	–	entrainment velocity
Q_{net}	–	net surface heat flux
Q_{swh}	–	penetrating shortwave radiation
A	–	horizontal eddy viscosity coefficient



e.g. see Frankignoul (1985, Rev. Geophysics)

Vertical Flux: entrainment and MLD (h)

Entrainment "To pull or draw along after itself"

$w_e >> w$ (Haney et al. 1983, Alexander 1992, +)

w_e from Turbulent Kinetic Energy (TKE) equation
(Niiler & Kraus 1977, Gaspar 1988)

When deepening:

$\partial h/\partial t = w_e + \nabla \cdot (hv)$

$w_e \approx M + hB - D / (Dr - S)$

Where

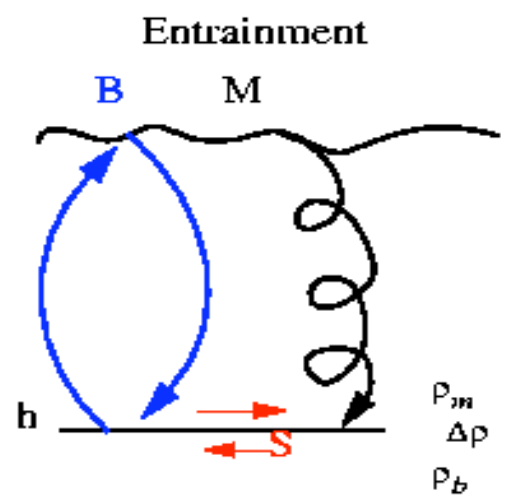
M - Mechanical Turbulence ($\sim u_*^{3} =$ (t/r) $^{3/2}$)

B - Buoyancy Forcing (Q_{net}, E-P)

D - Dissipation (eh)

Dr - Density jump at base of the ML

S - Shear across ML (not in all models)



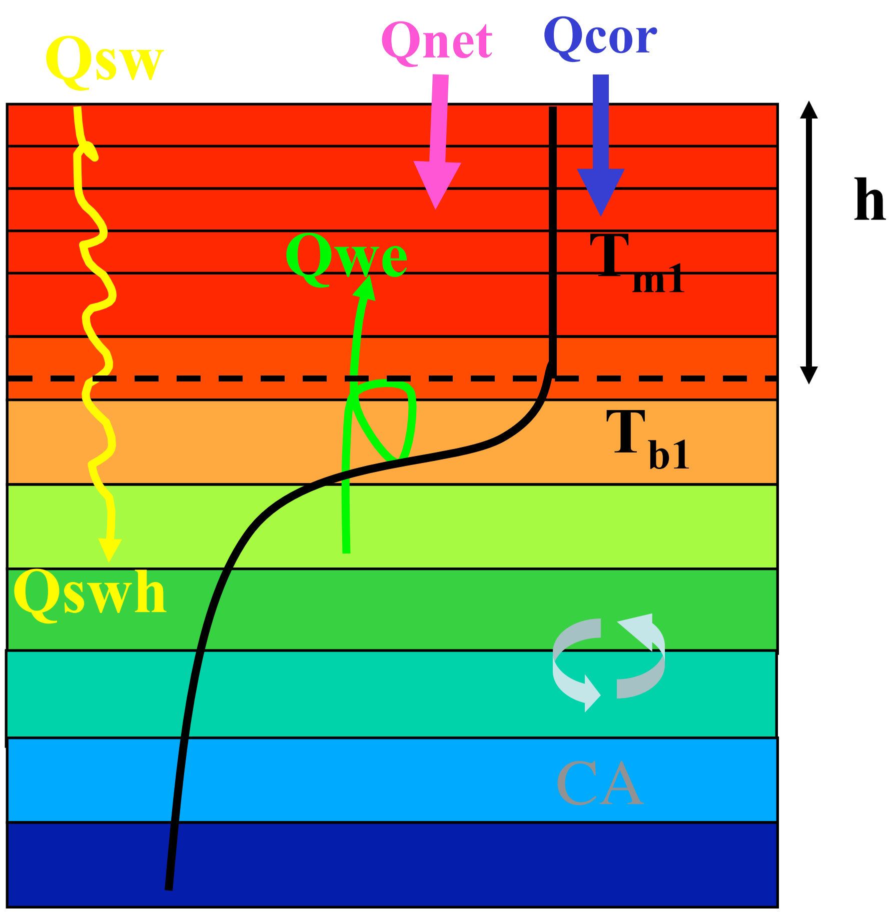
When Shoaling:

$w_e = 0$ (no detrainment, h reforms closer to the surface)

$h = M / (B - e)$

Mixed Layer Ocean Model

$$\frac{\partial T_m}{\partial t} = \frac{Q_{net} + Q_{cor}}{\rho c h} - \frac{Q_{swh}}{\rho c h} + \frac{W_e \Delta T}{h} + CA - \frac{\kappa \partial T}{h \partial z}\bigg|_{z=-h}$$



Alexander et al. 2000

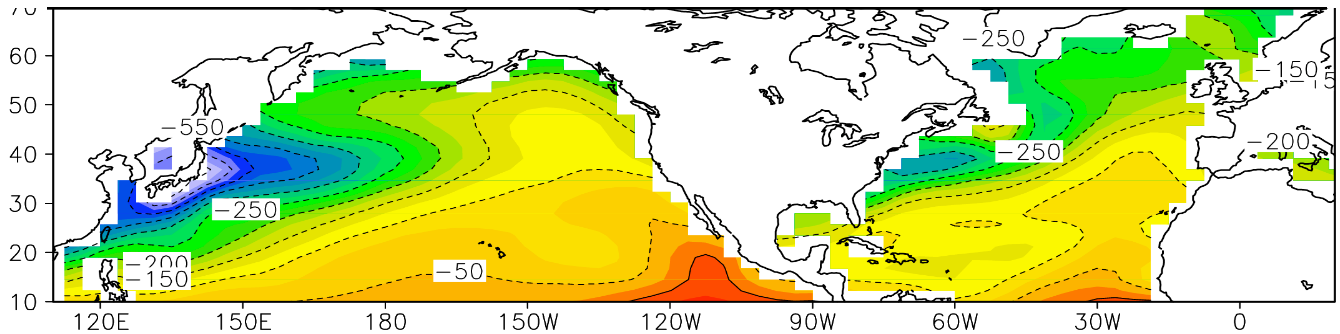
- Qcor - flux correction
- $\Delta T = (T_b - T_m)$, temperature jump
- CA - convective adjustment
- Grid of Mixed layer Models (MLM) are coupled to an AGCM to explore role of the above terms in the SST (TM) equation.
- Some terms are hard to obtain from observations.

Mean ML Budget terms (Wm^{-2}) in January

From an AGCM couple to a mixed layer ocean model

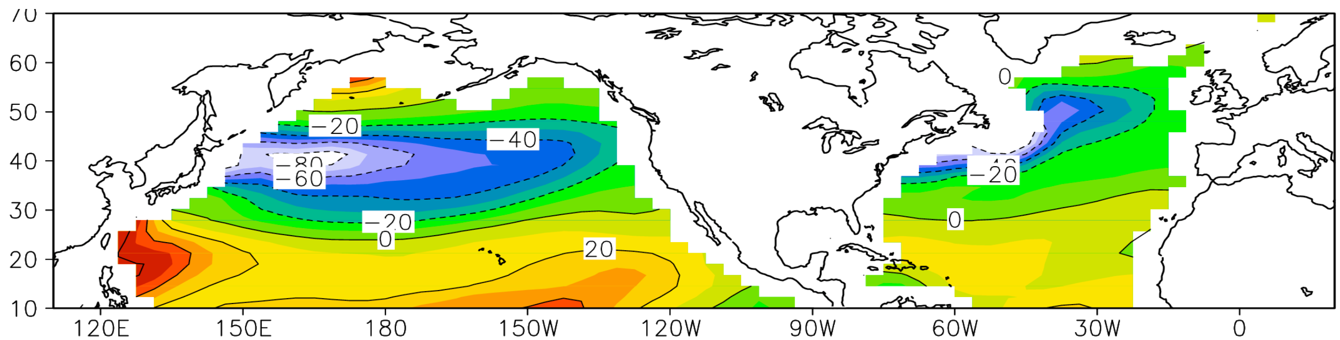
Surface Flux

Q_{net}



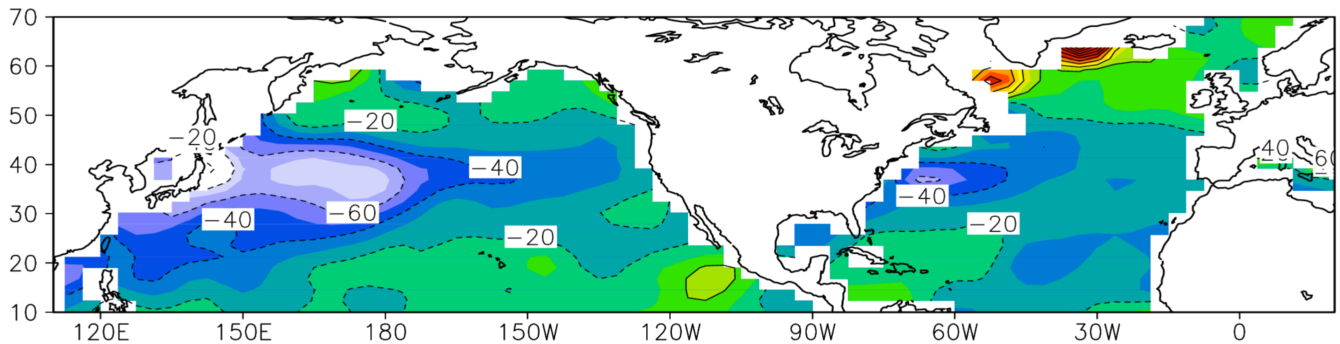
Ekman

$Q_{ek} = \rho c \mathbf{v}_{ek}(\nabla T_m)$

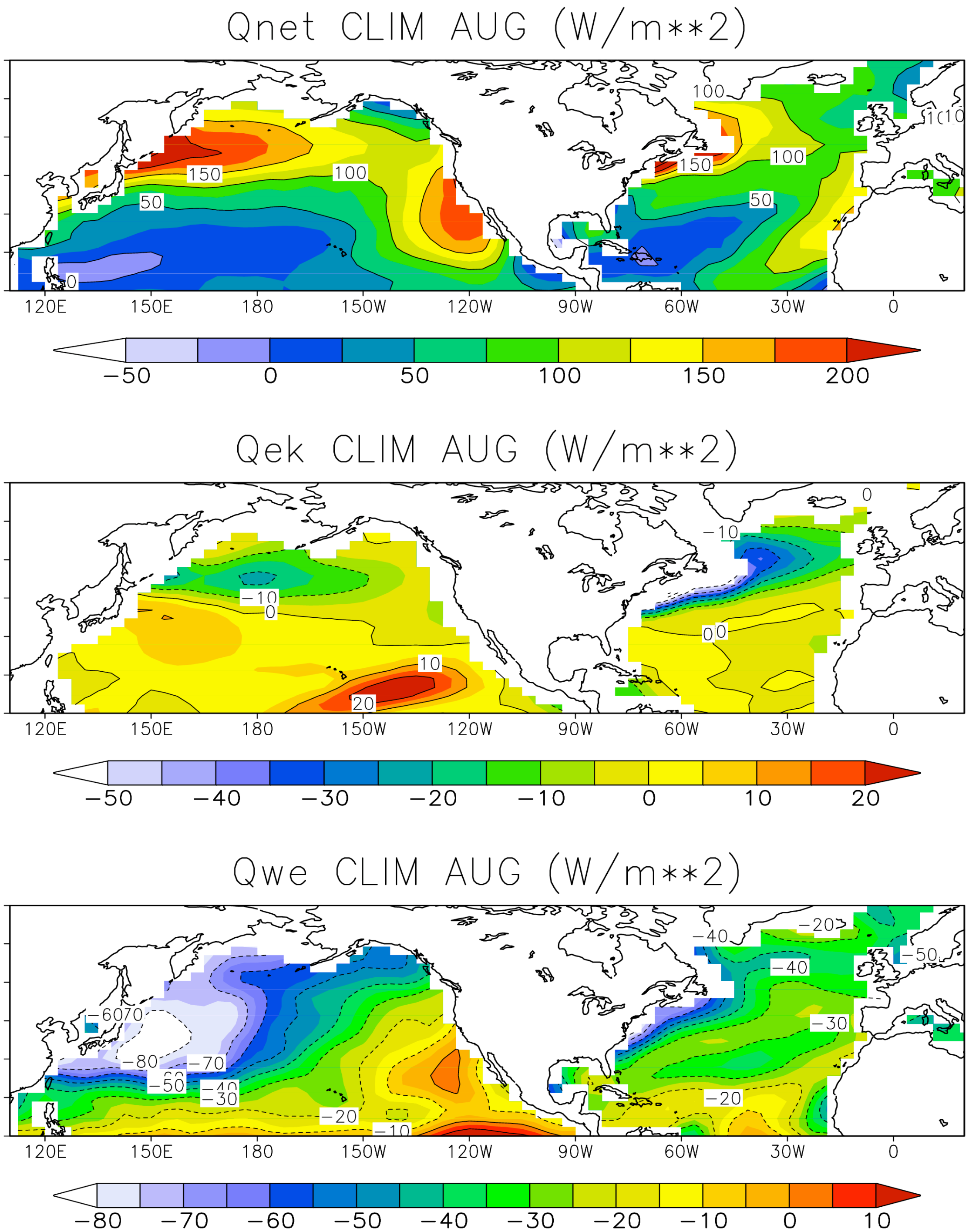


Entrainment

$Q_{we} = \rho c w_e(T_b - T_m)$

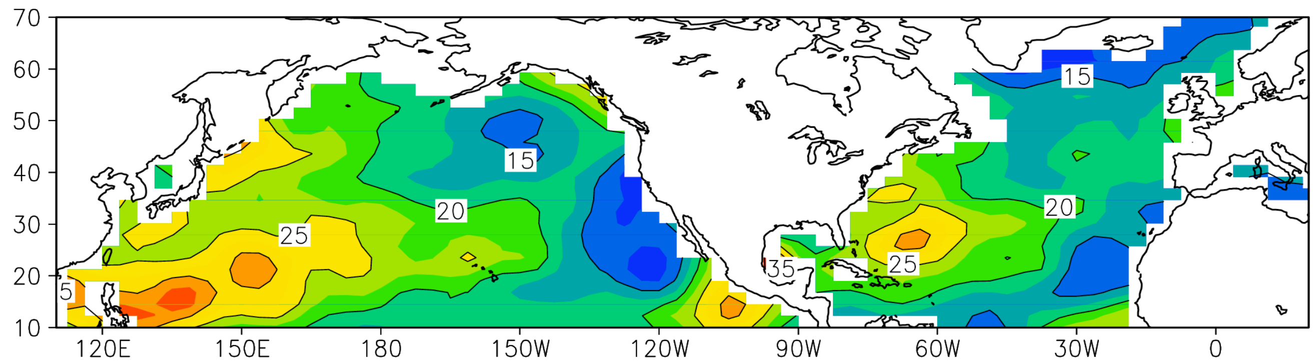


Mean Mixed Layer Budget terms (Wm^{-2}) in August



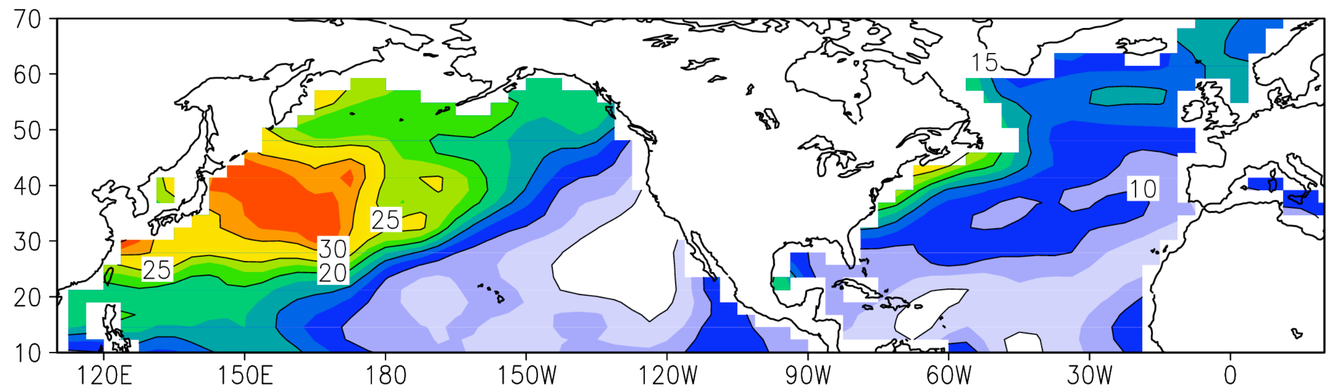
Standard Deviation of Fluxes in August

Q_{net}
W m^{-2}

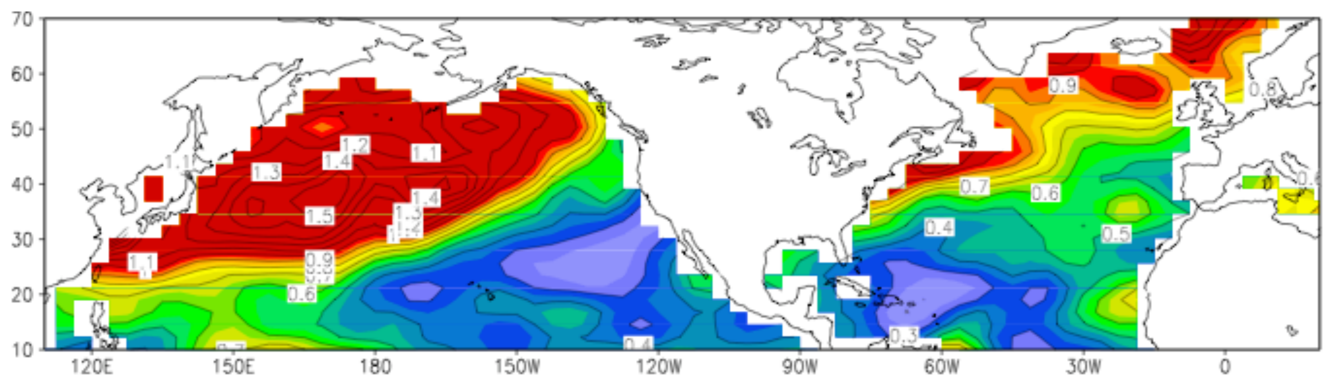


Q_{we}

W m^{-2}



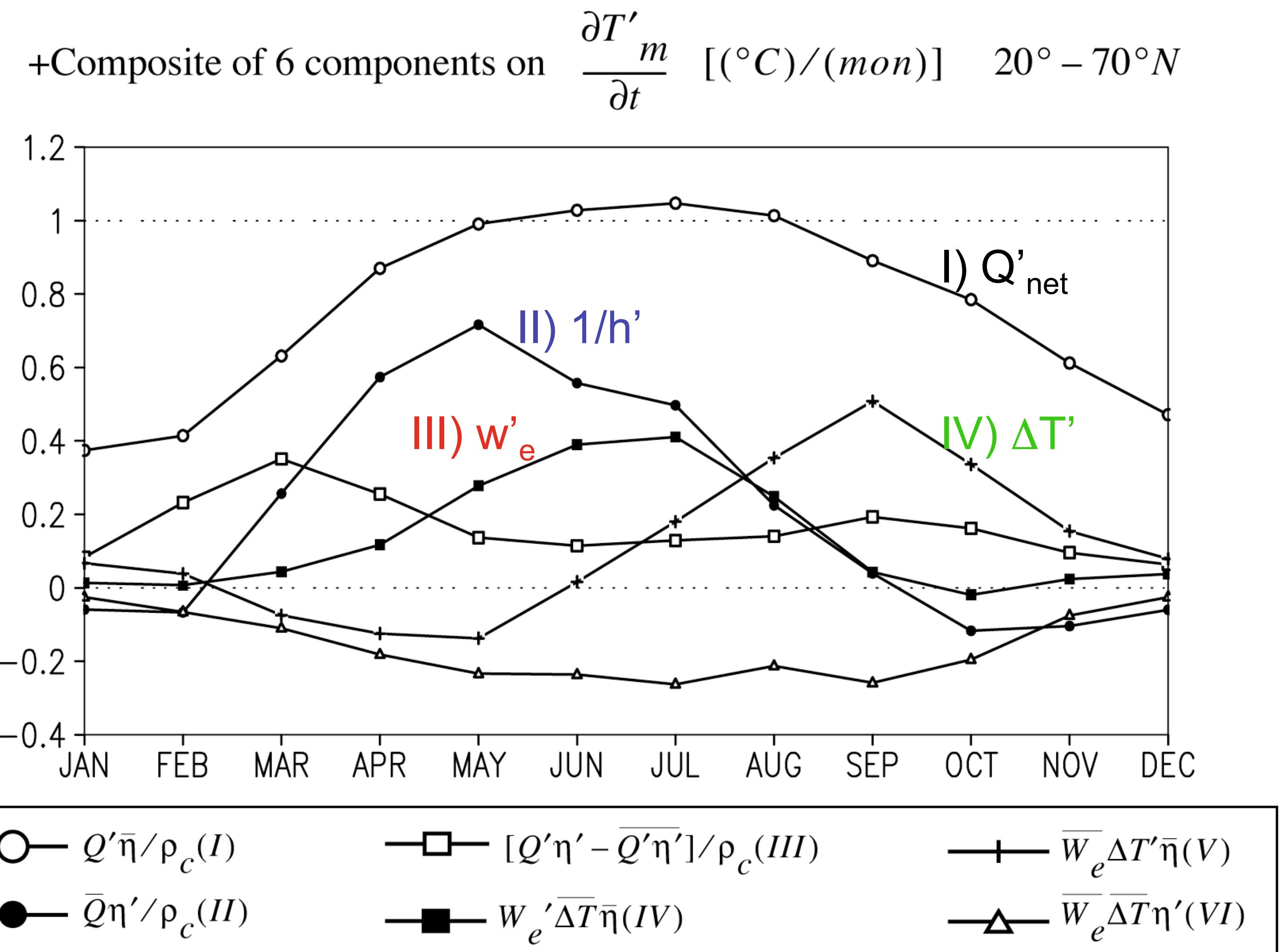
Q_{we} /
Q_{net}



Q_{we} / Q_{net} ~.2 - 0.5 in winter

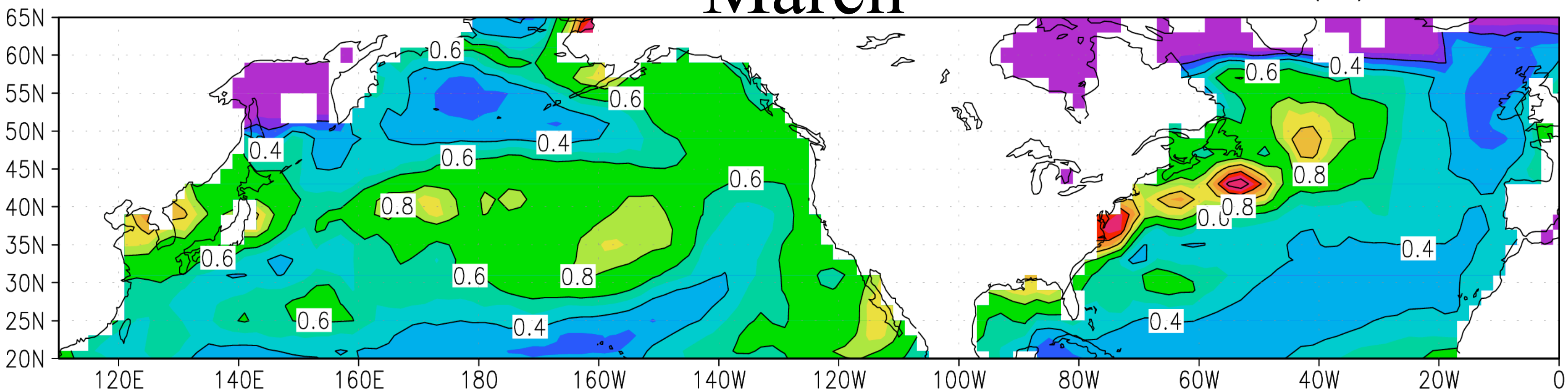
Terms in the SST' heat budget role in rapidly warming temperatures

Expand variables into time mean (-), and departure ('), $\eta = 1/h$, $\Delta T' = (T_b - T_m)'$

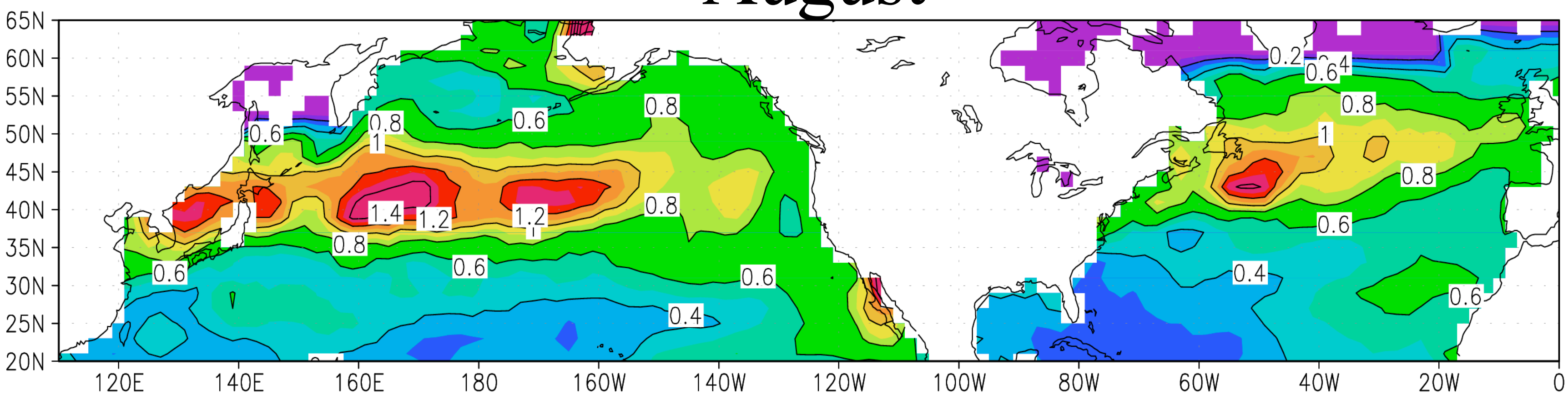


Observed Standard Deviation of SST Anomalies (°C)

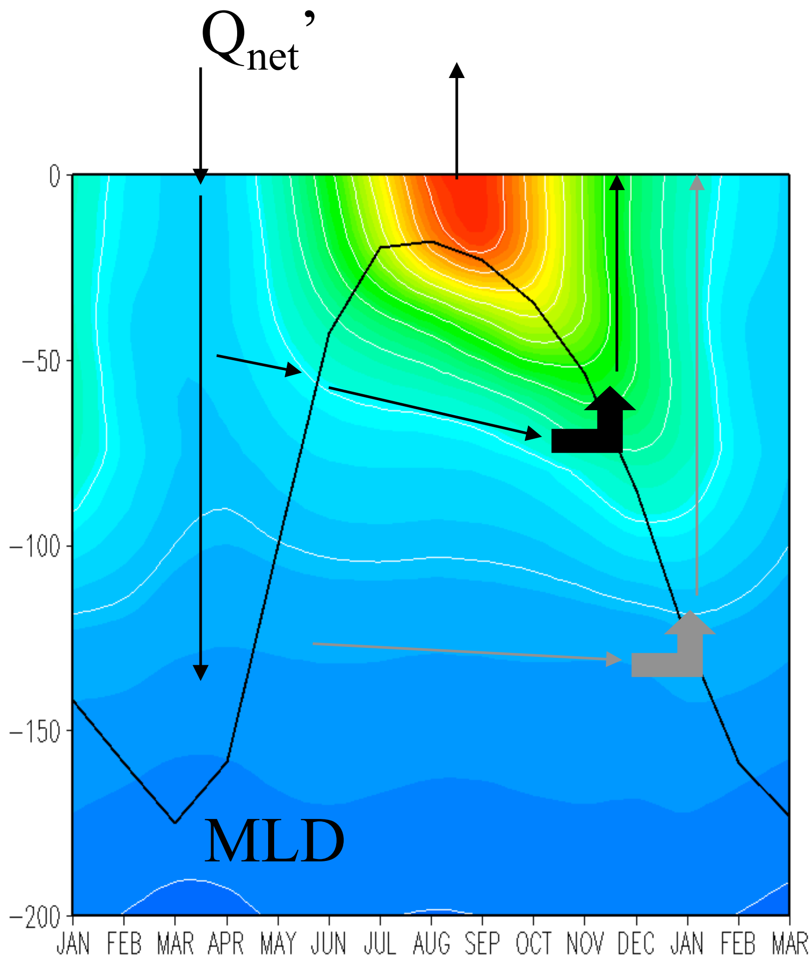
March



August



The Reemergence Mechanism



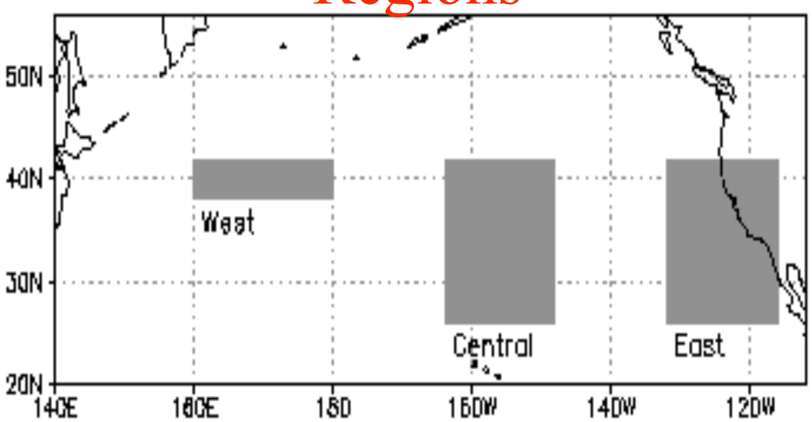
- Winter Surface flux anomalies
- Create SST anomalies which spread over ML
- ML reforms close to surface in spring
- Summer SST anomalies strongly damped by air-sea interaction
- Temperature anomalies persist in summer thermocline
- Re-entrained into the ML in the following fall and winter

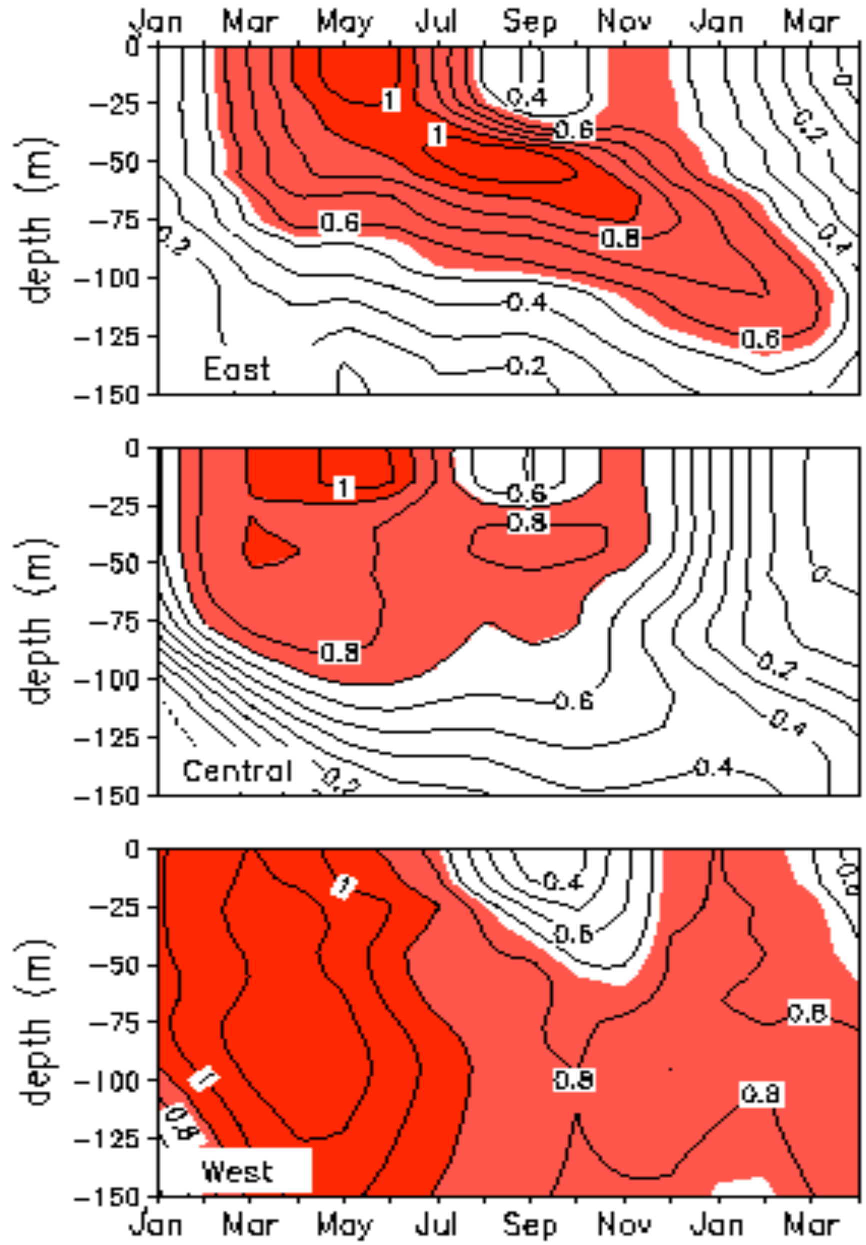
Namias and Born 1970, 1974;
Alexander and Deser (1995, JPO); Alexander et al. 1999
+

Reemergence in three North Pacific regions

Regression between SST anomalies in April-May with monthly temperature anomalies as a function of depth.

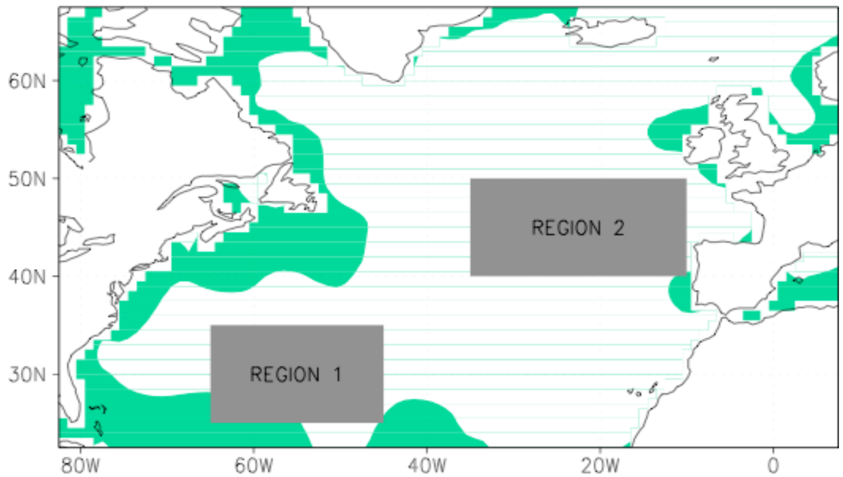
Regions



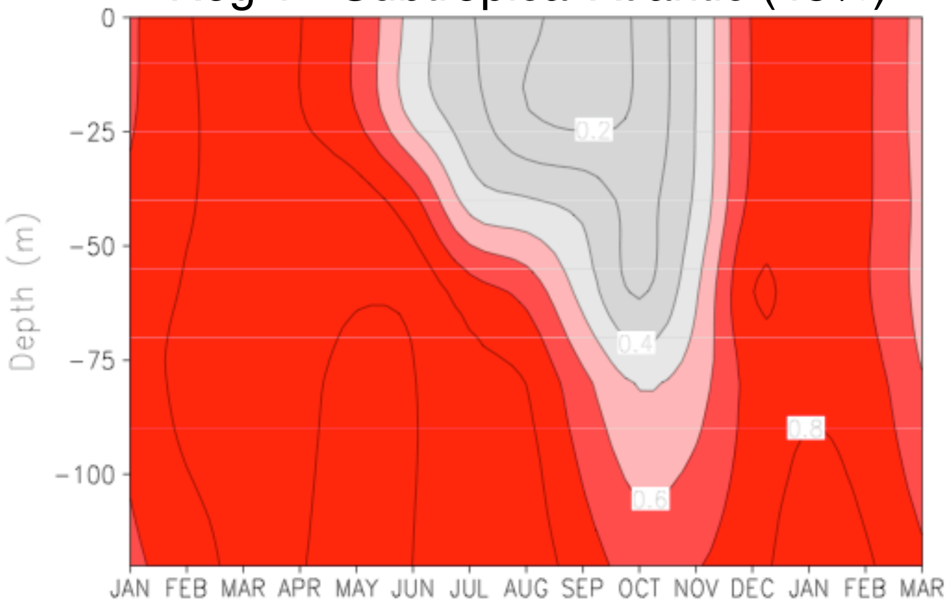


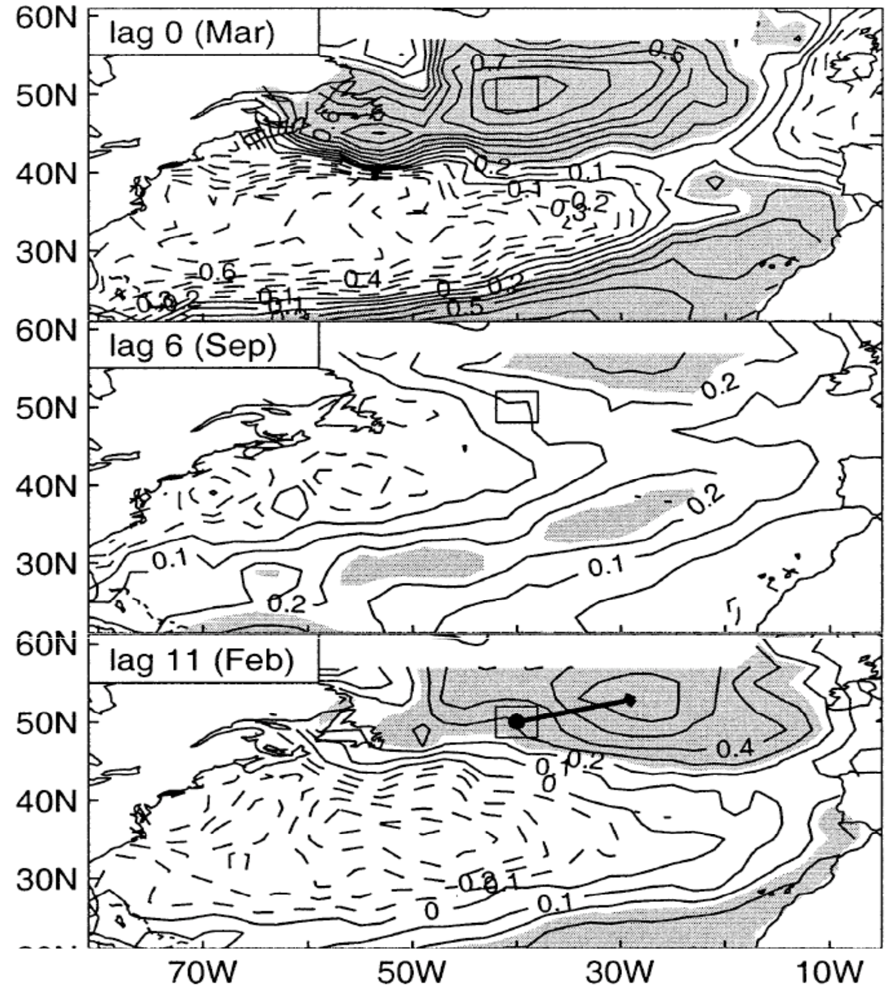
Alexander et al. (1999, J. Climate)

North Atlantic Regional Time Depth EOFs



Reg 1 - Subtropical Atlantic (48%)





Remote reemergence:Temperature anomalies advected by currents. *de Coetlogon and Frankingoul (2003, J.Climate)*

Impact of reemergence on SST Persistence:
Extending the Stochastic SST Model

Stochastic Model for SSTs
Hasselmann and Frankignoul (1977)

• Heat fluxes associated with weather events random (stochastically) force ocean

• Ocean integrates forcing slowly developing SST anomalies

• Heat fluxes damp these anomalies

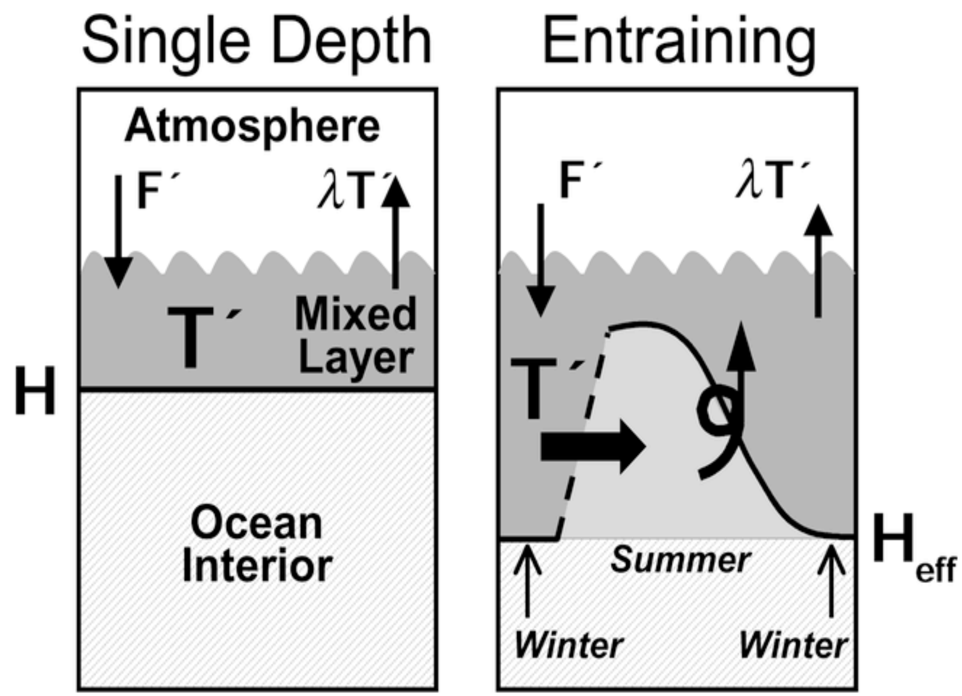
$$\rho ch \frac{dT'_m}{dt} = F' - \lambda T'_m$$

F' forcing, λ linear damping coefficient

$$r(\tau) = \exp\left[-\lambda\tau/\rho ch\right]$$

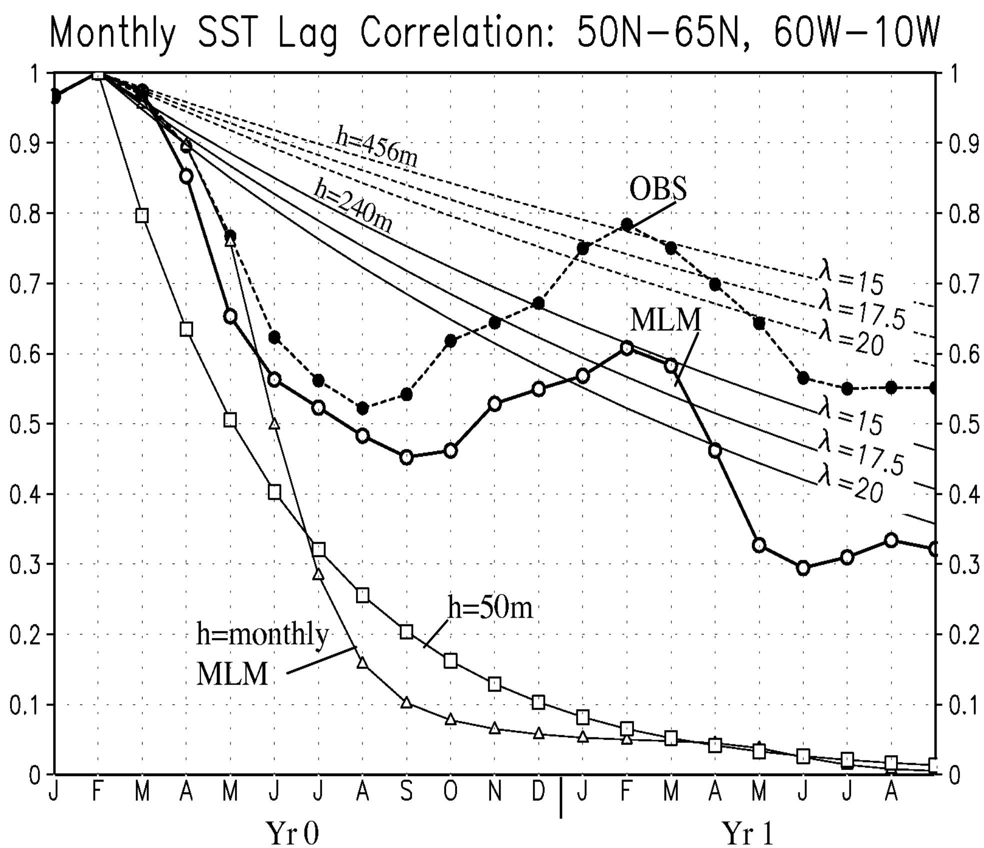
r autocorrelation at lag τ

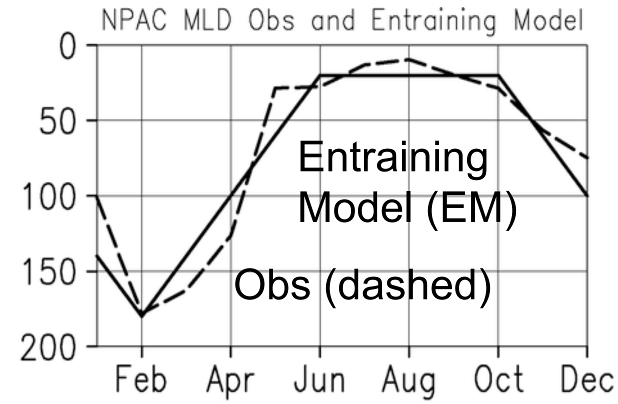
Originally *h* set as a constant

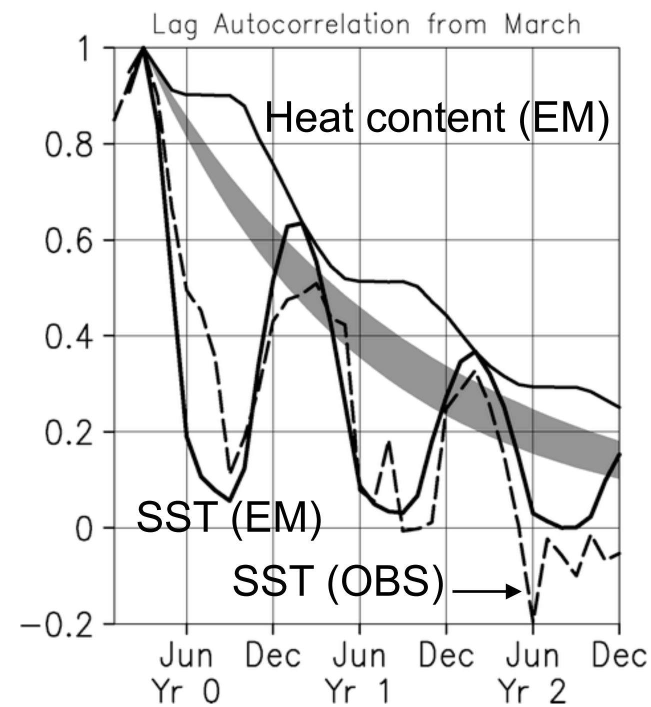


SST Autocorrelation w/wo variable MLD

North Atlantic







Deser et al. 2003 J. Climate

Heff = winter MLD for interannual variability in a stochastic model

Do the reemerging SST anomalies impact the atmosphere?

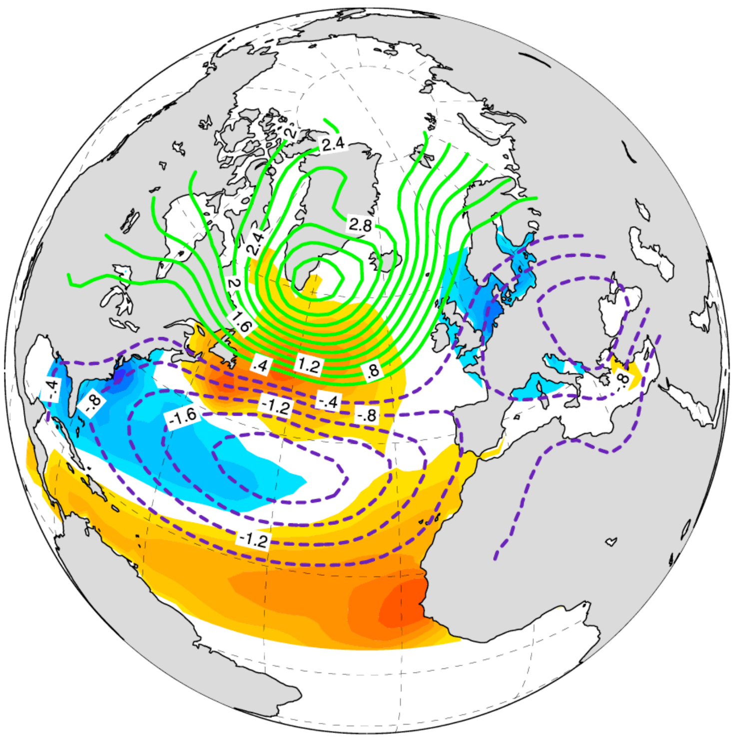
- First examine relationship between atmospheric circulation and SSTs in the Atlantic to determine leading pattern of SSTs forced in winter and see if they reemerge

- Then use AGCM (NCAR CAM2) coupled to a mixed layer ocean model (predicts h)

- *Cassou, Deser and Alexander (J Climate 2007)*

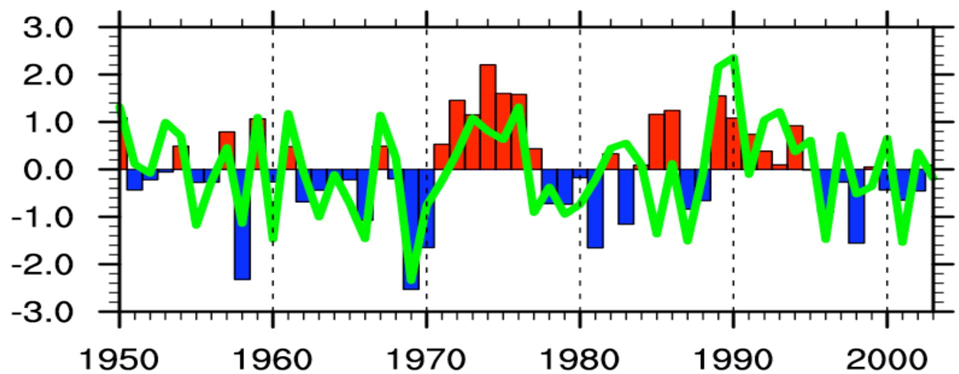
Atmosphere forcing the ocean in winter: NAO & the Atlantic SST tripole

March SST EOF1 (shade)
Regressed JFM SLP (contour)



NCEP MSLP [1950-2003]

PC time series: March SST (bars), JFM MSLP (line)

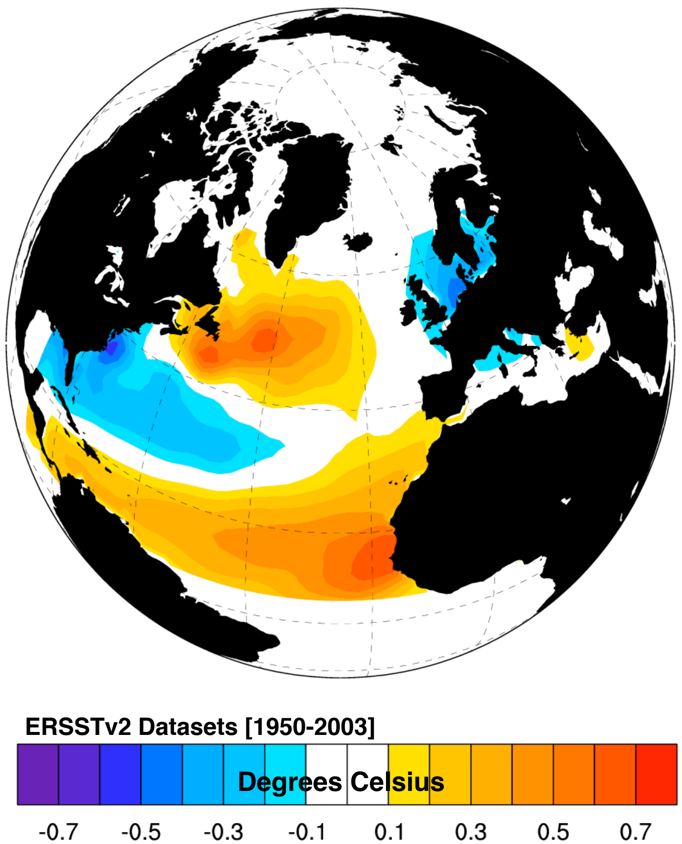


Correlation=0.63

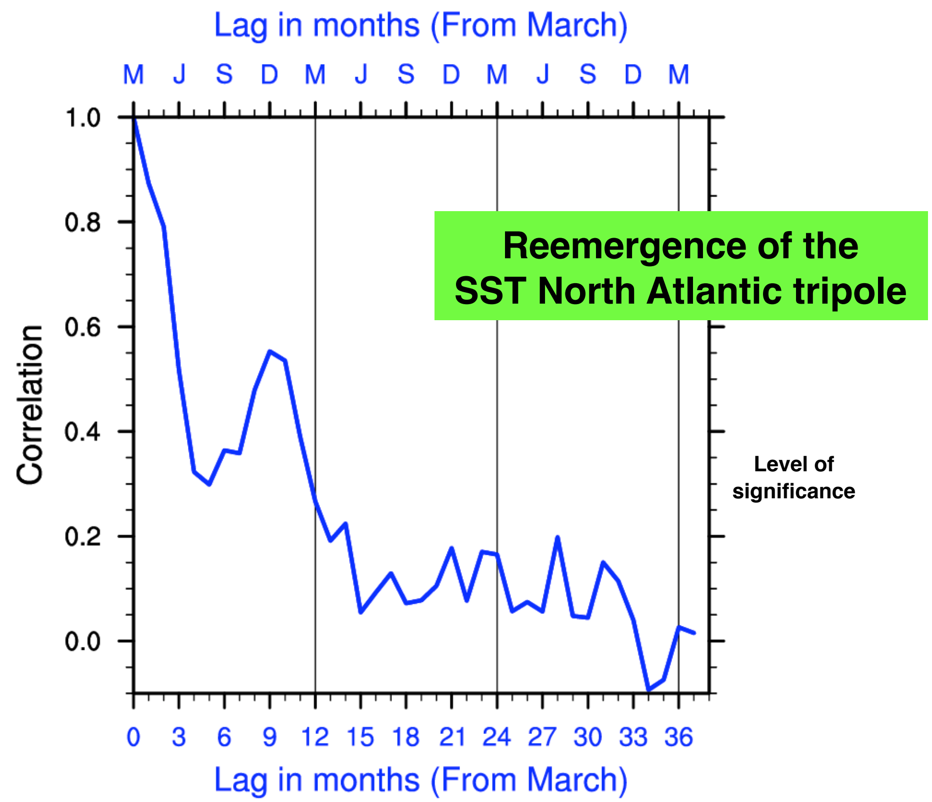
e.g. Deser and Timlin (1997), J.Clim.

Reemergence of SST Tripole

Leading EOF of March SST



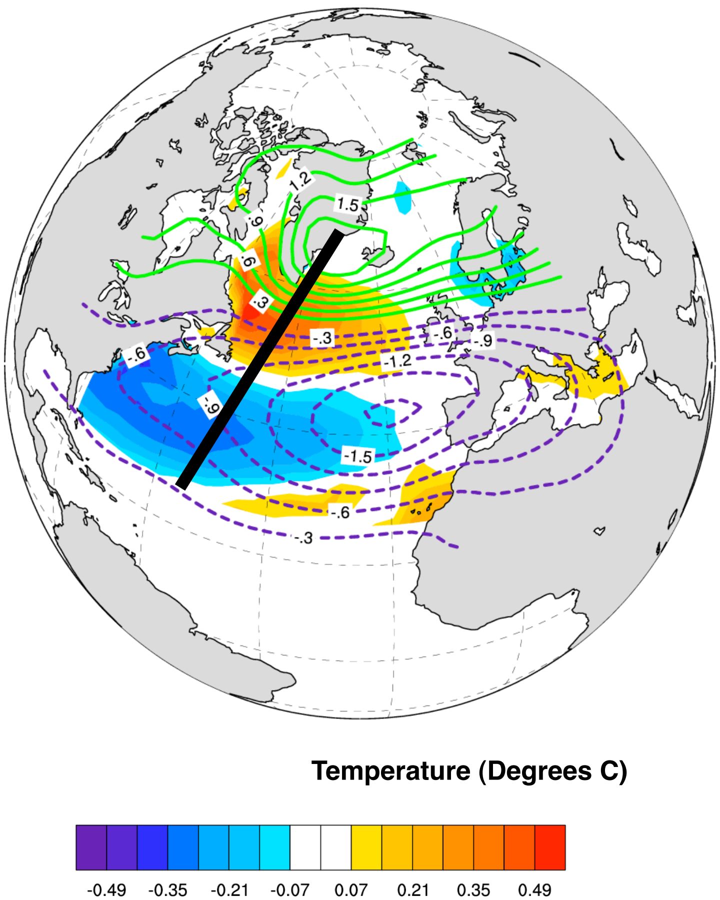
Auto-correlation of EOF PC time series



Watanabe and Kimoto (2000); Timlin et al. 2002,
Deser et al 2003 (J.Clim), De Coetlogon and Frankignoul 2003 : all J. Climate

Experimental Design

FMA Sea Level Pressure (contours)
JAS temperature at 50m depth (shading)



- Use SVD between SLP Winter & Ocean Temp summer in the control run to obtain ocean conditions associated with NAO at depth in the following summer.

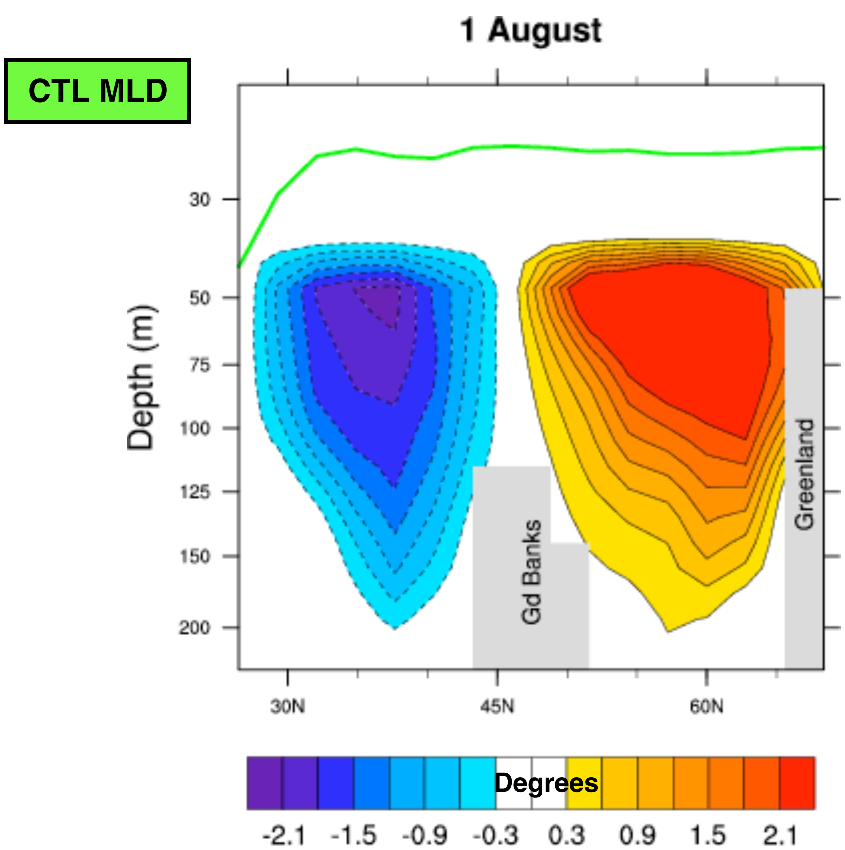
- Specify subsurface (40-450m) temperature anomalies on August 1

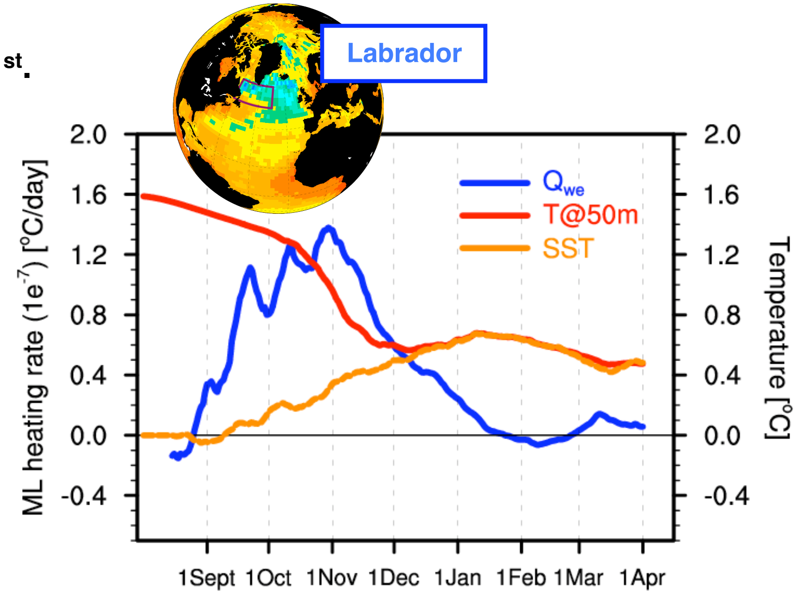
- Run model integrations for 1 year Aug 1 – July 31, with different initial atmospheric conditions:
  - 60 runs with positive polarity,
  - 60 with with negative polarity.

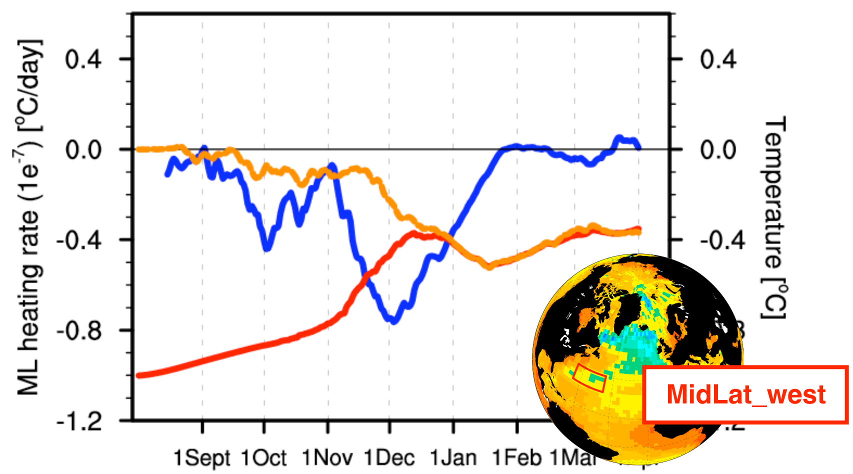
- Response: ensemble average of the positive - negative integration

Timing of the Reemerging Signal

Evolution of the REM anomalies over a year starting in August 1st.
Section @ [60º - 40ºW] from 25º to 68ºN



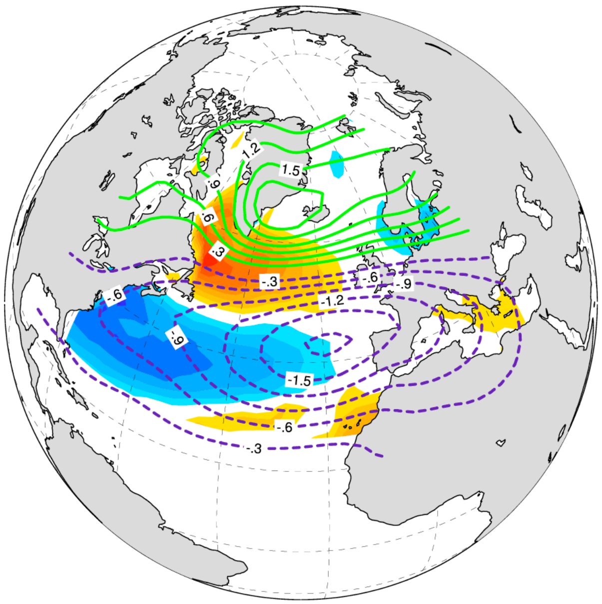




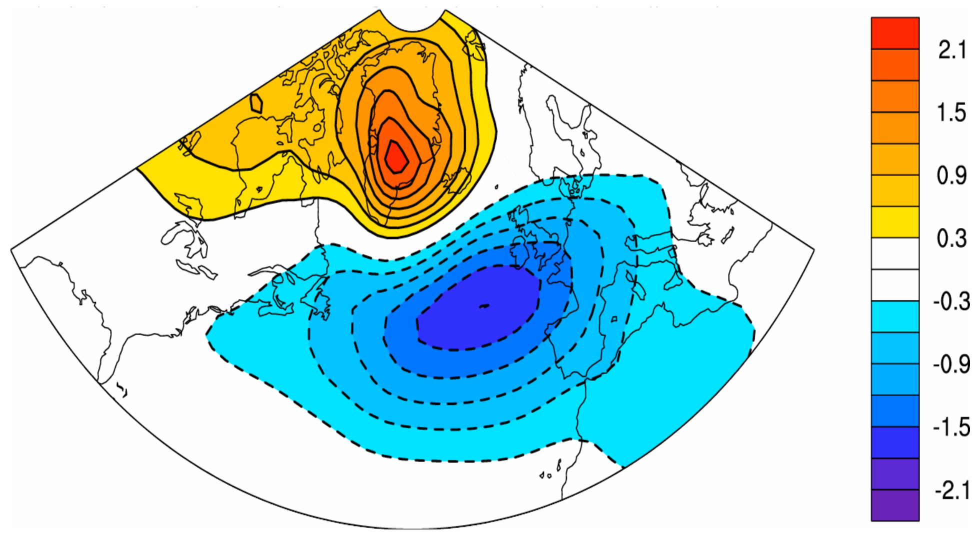
Reemergence occurs in REM in Oct-Nov-Dec

Winter (NDJFM) Sea Level Pressure Response

Forcing



SLP Response



Modest (~20%) but significant SLP response that acts as a positive feedback (e.g., in this model, reemergence enhances the winter-to-winter persistence of the North Atlantic Oscillation).

Relation to Observations?

Lag Autocorrelation of the detrended 3-month observed NAO Index

Yr1 \ Yr2	NDJ_2	DJF_2	JFM_2
NDJ_1	0.11	0.14	0.10
DJF_1	0.19	0.25	0.17
JFM_1	0.32	0.26	0.09

Consistent w/ the Reemergence forcing

• The Model results indicate that reemerging tripole SST anomalies favor the same phase of the NAO that created them the previous winter.

Summary

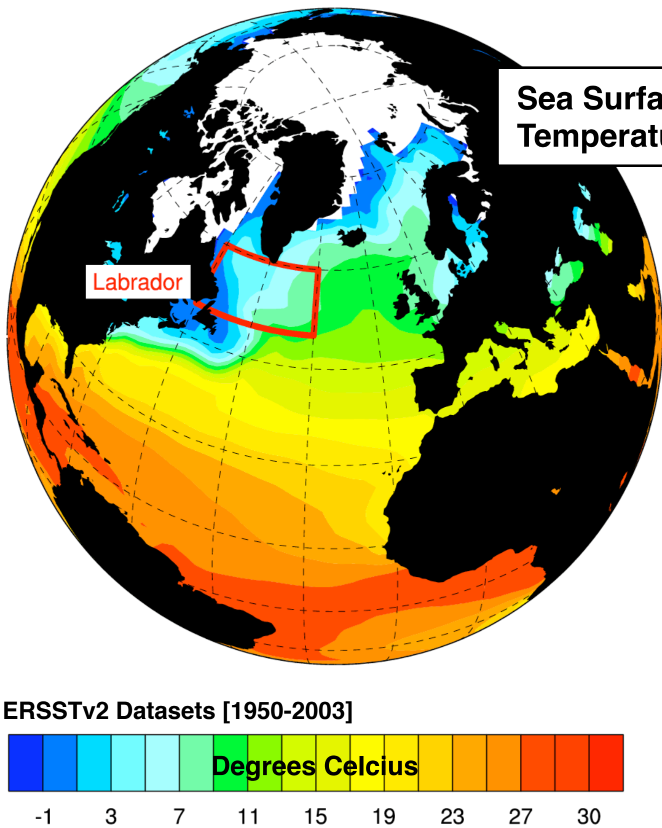
- Entainment & concept of MLD important for SST evolution
  - E.g. SST anomalies larger in summer than winter due to shallow MLD
- Reemergence
  - Adds predictability for SST and potentially for the atmosphere as well
  - Extends the stocashtic model for SSTs
  - Also occurs for salinity
  - Reemergence extends oceanic impact of atmospheric teleconnections
- Other roles for mixing
  - Interaction with the deeper ocean
    - Subduction (ML water leaves the surface)
    - Rossby wave propagation to the Kuroshio region:
      - Remix temperature anomalies due to thermocline variability back to the surface
  - Biological
    - Bring nutrients to the surface (if not enough nutrient limited)
    - Mix phytoplankton if too much (light limited)

Additional Slides

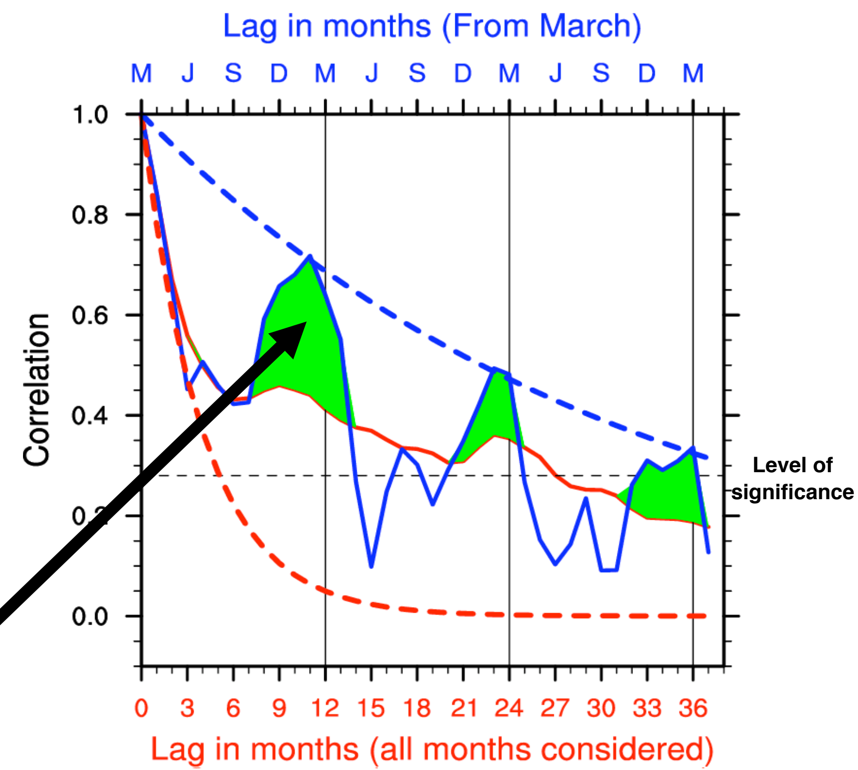
- More on the experiment of reemergence in the Atlantic
- Rossby waves that are

1. What is the oceanic reemergence?

2. Surface signature of reemergence in the Labrador Sea



Auto-correlation of the Labrador SST time series *(Starting from March),* **e.g. for lag=1, March and April time series are correlated, for lag =2 March and May etc.**



Deser et al. 2003 (J.Clim)

Reemergence of the late winter SST anomalies a year after

Auto-correlation of the Labrador SST time series *(all months considered),* **e.g. for lag=1, Jan50/Feb50/…/Dec00 values are correlated with Feb50/Mar50/…/Jan01 values**

Atmosphere-Ocean Ice Model

Atmospheric GCM

- NCAR CAM2–T42 resolution

Ice

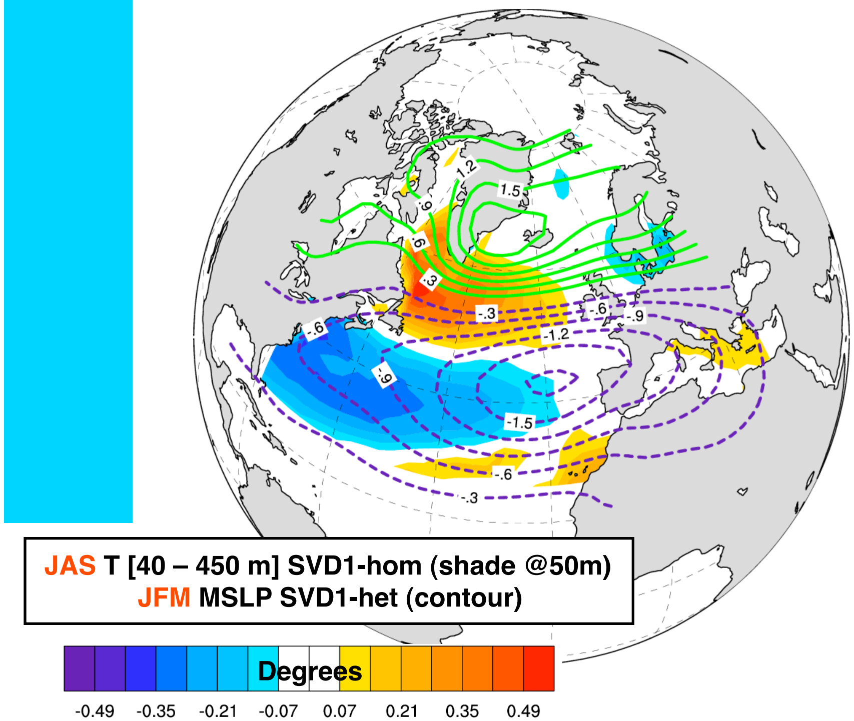
Thermodynamic portion of NCAR CSIMv4

Ocean

Mixed layer Model (MLM)

- An individual column model with a uniform mixed layer
- Atop a layered model that represents conditions in the pycnocline
- Prognostic ML depth
- Same grids as the atmosphere (128 lon x 64 lat)
- 36 vertical levels (from 0m to 1500m depth)
  - higher resolution close to surface and a realistic bathymetry
- Flux correction needed to get reasonable climate
- Cassou et al. 2007 J Clim; Alexander et al. 2000 JGR, Alexander et al 2002 – J.Clim ; Gaspar 1988 – JPO

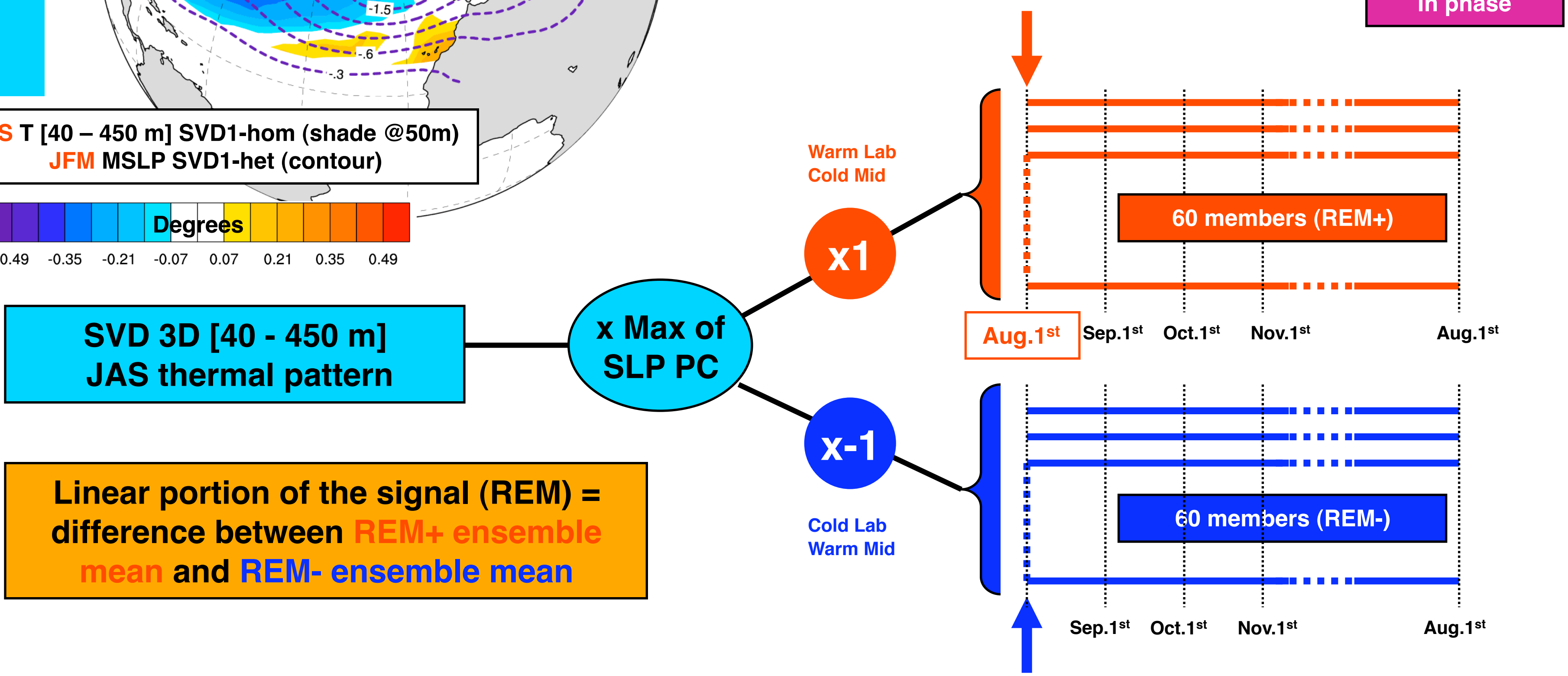
2. Link between summer subsurface anomalies and previous SLP



Lagged 3D SVD between previous winter SLP [20°-85°N/90°W-30°E] and July-Sep. (JAS) ocean temperature between 40 – 450 m and for [25°-85°N] i.e. tropics excluded in CTL

Season	NDJ	DJF	JFM	FMA	MAM	AMJ	MJJ	JJA	JAS
Cov (%)	**73**	**79**	**79**	**84**	**64**	**62**	57	53	35
Corr.	0.50	**0.62**	**0.62**	**0.59**	0.45	**0.64**	**0.64**	**0.61**	0.37

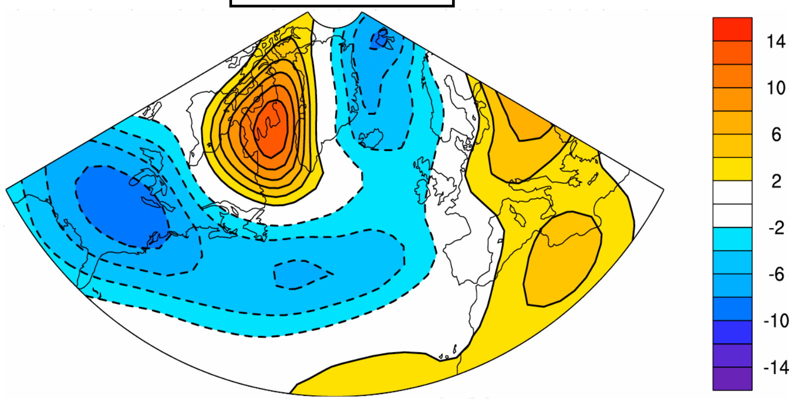
Subocean/Atm In phase



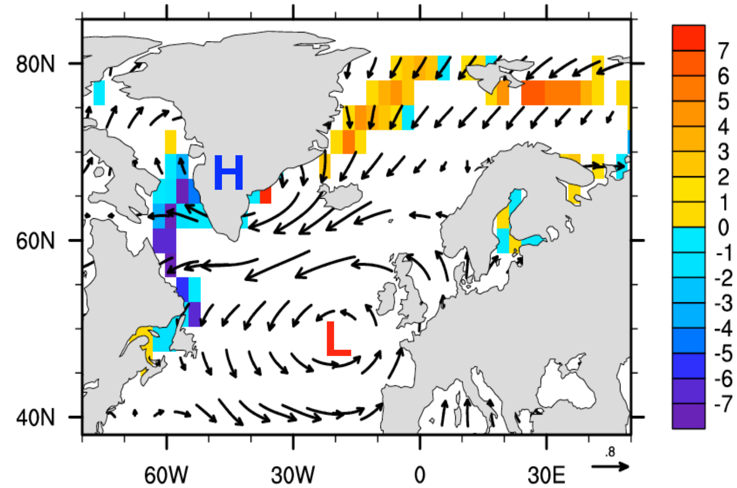
Linear portion of the signal (REM) = difference between REM+ ensemble mean and REM- ensemble mean

The Mean NDJFM Atmospheric Response

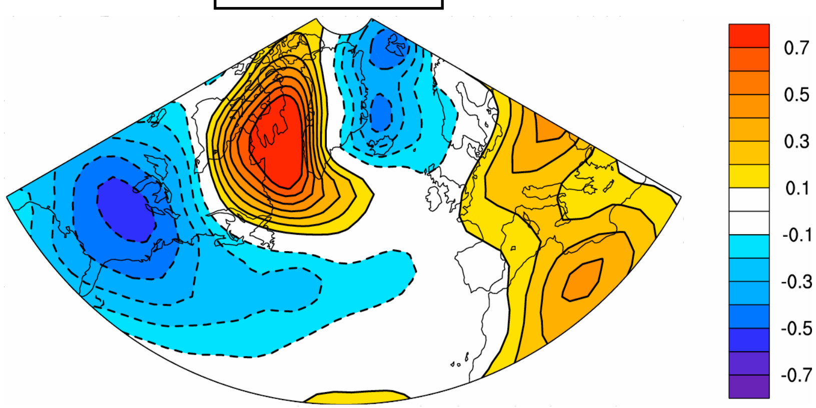
Z 500 (m)



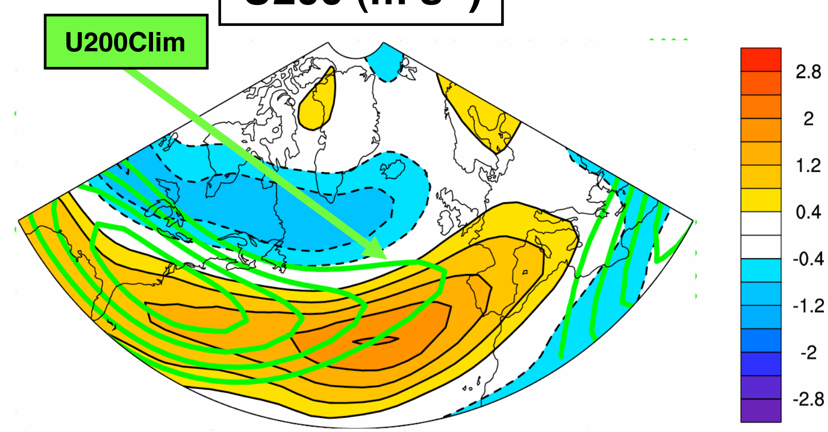
Surface wind & Ice concentration



T850 (°C)

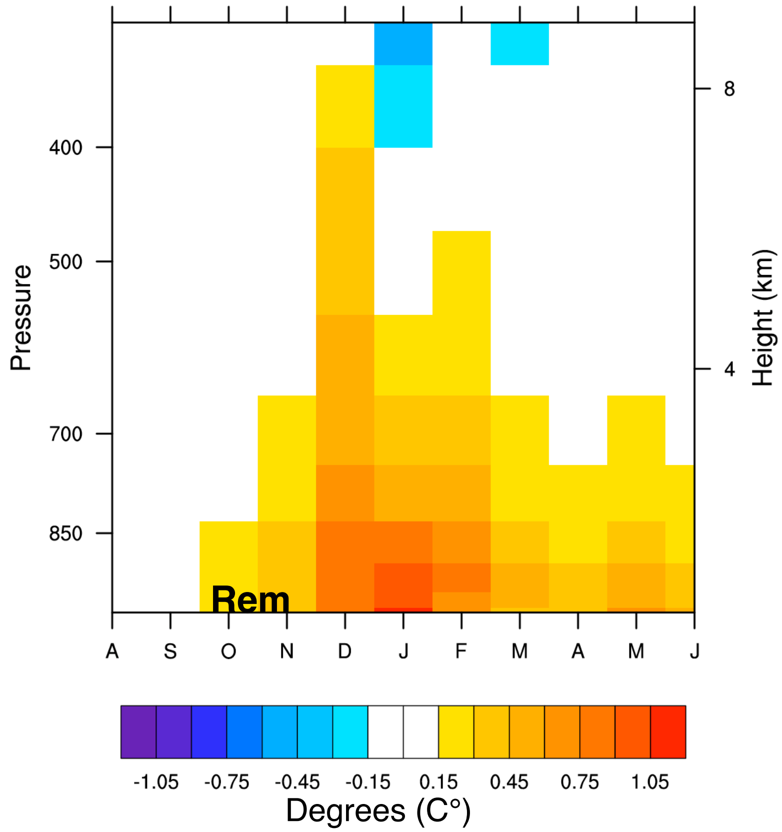


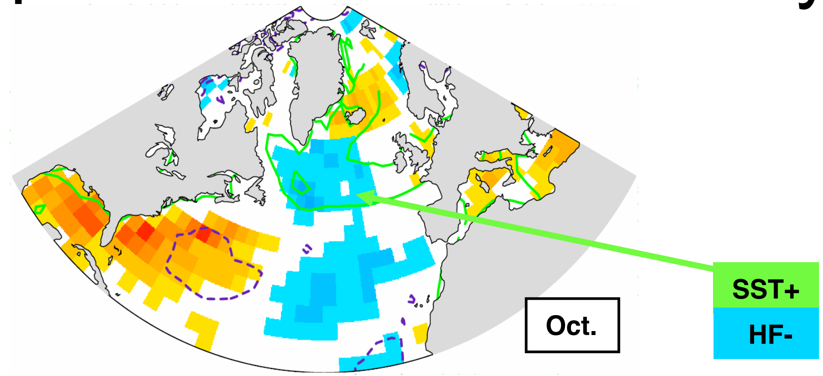
U200 ($m\ s^{-1}$)



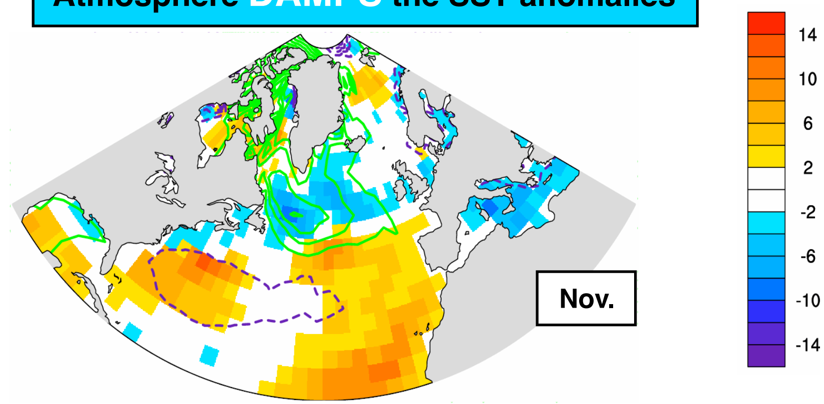
Air-Sea Feedback & Response w.r.t. Seasonal Cycle

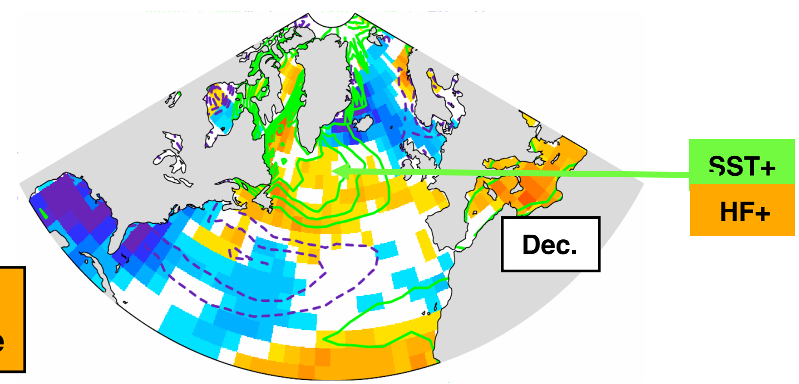
Atmospheric Vertical profile of Temperature Anomalies in Labrador Region





Early stage of the Reemergence:
Atmosphere DAMPS the SST anomalies

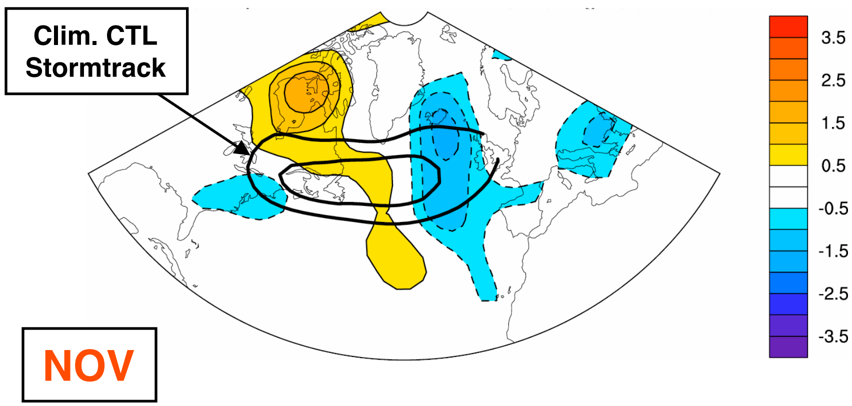


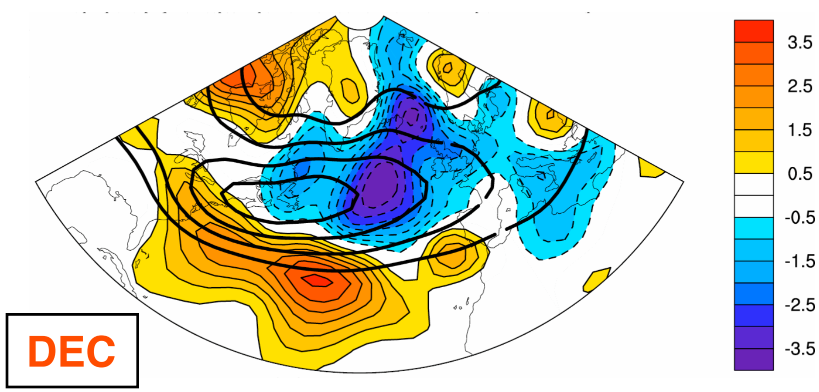


Late stage of the Reemergence:
Positive feedback of the Atmosphere

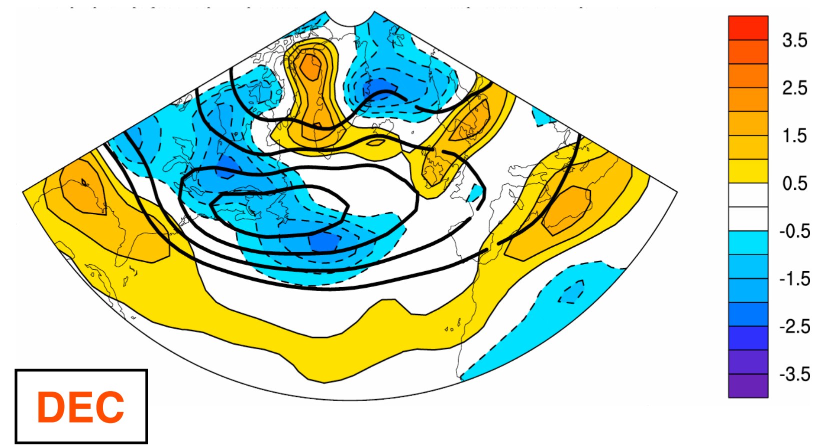
Storm Track Changes

2-8 day band pass filtered Z500 (m) Variance



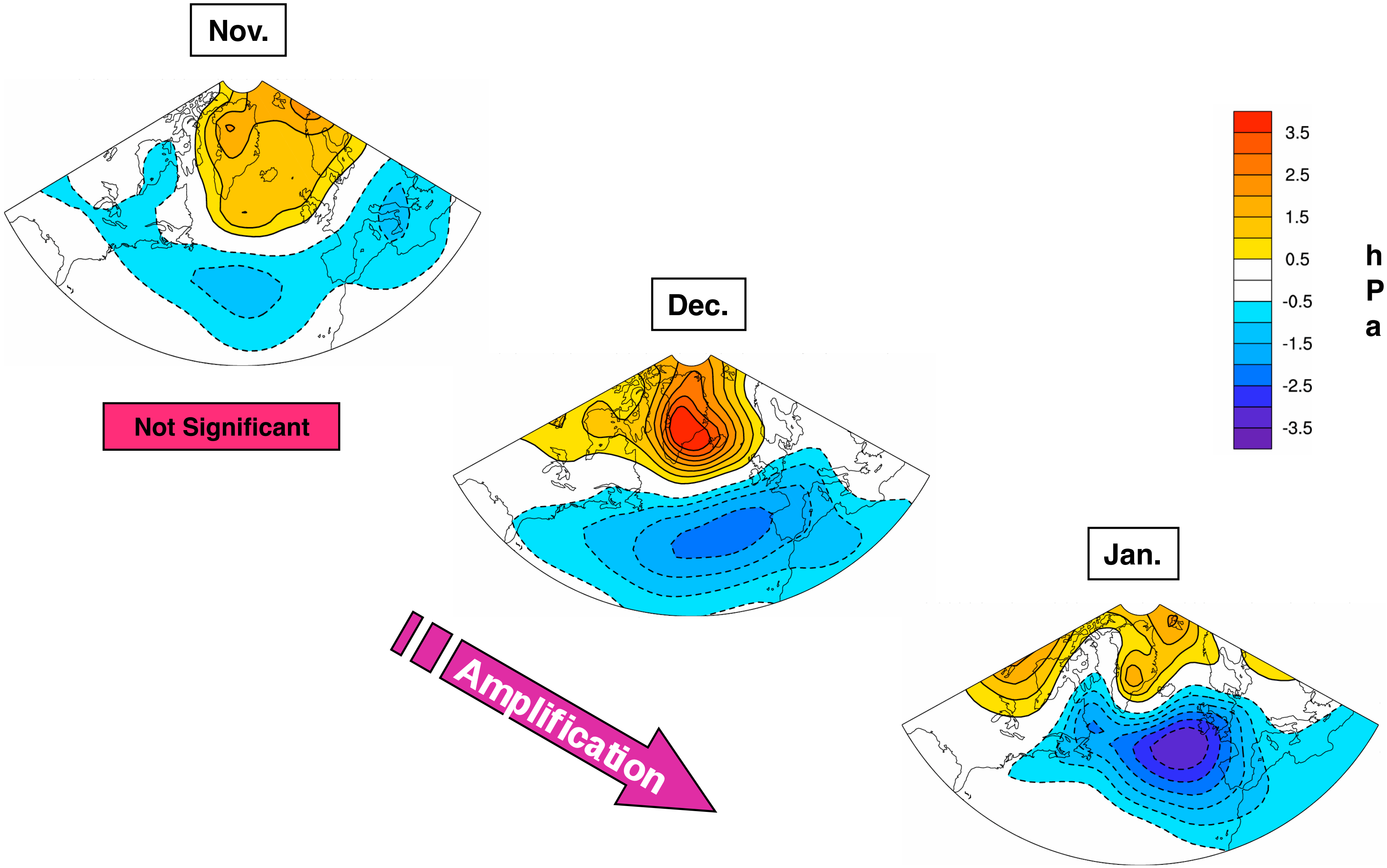


Eady Baroclinic Growth Rate @850 hPa

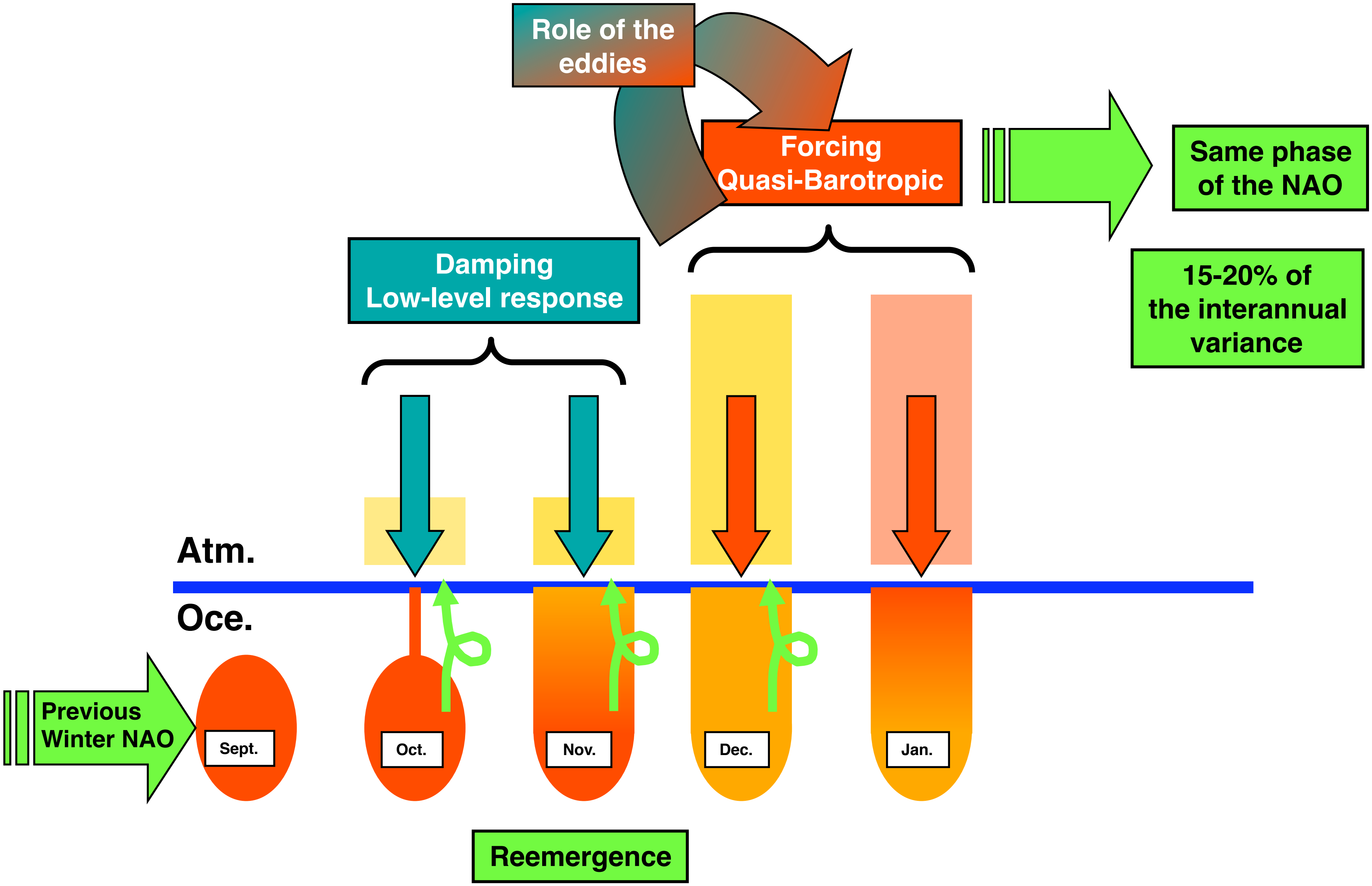


Storm changes timing consistent with positive Feedback on the large scale flow in December

Monthly Evolution of the SLP Response



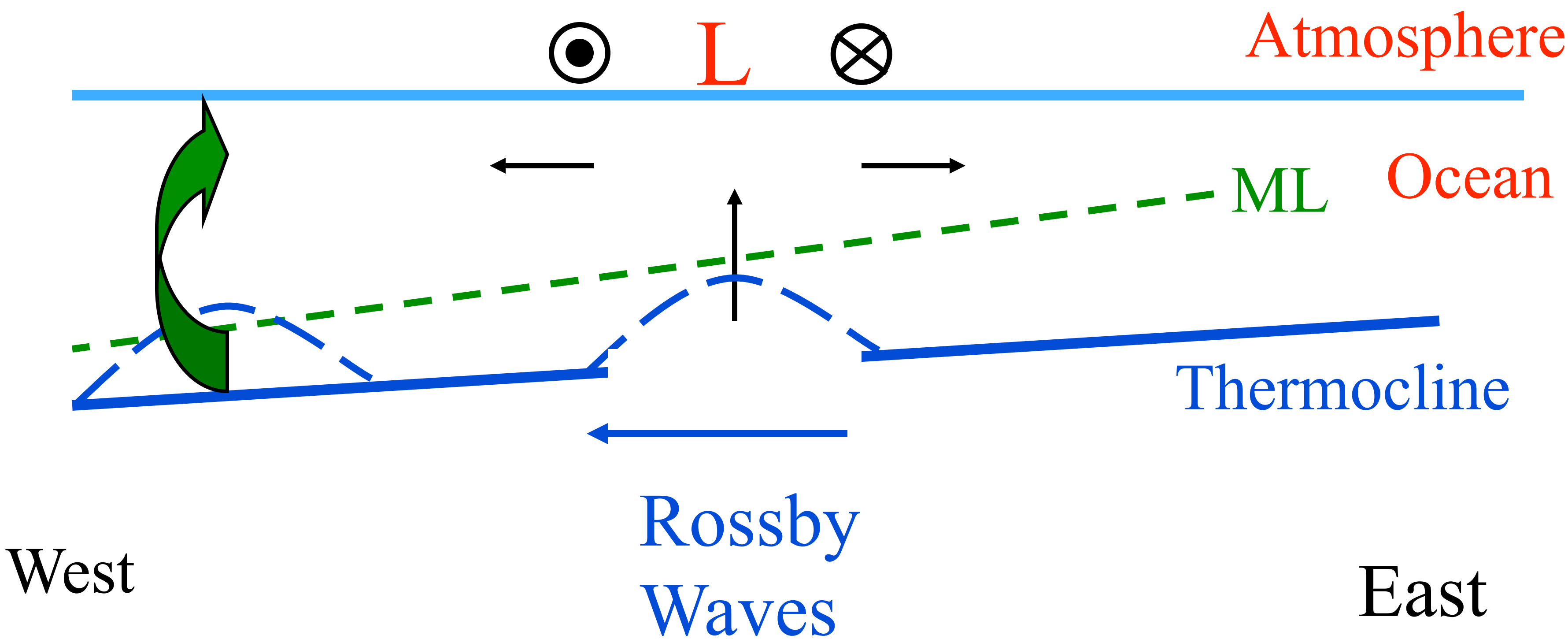
Schematic of the REM response



Additional Topics

- The flux components and their variability
- Schematic of the mixed layer model
- Pattern of atmospheric circulation (SLP) and the underlying fluxes)
- Basin-wide reemergence
- The Pacific Decadal Oscillation
- Wind generated Rossby waves and its relation to SSTs
- The Latif and Barnett mechanism for the PDO and “problems” with this mechanism

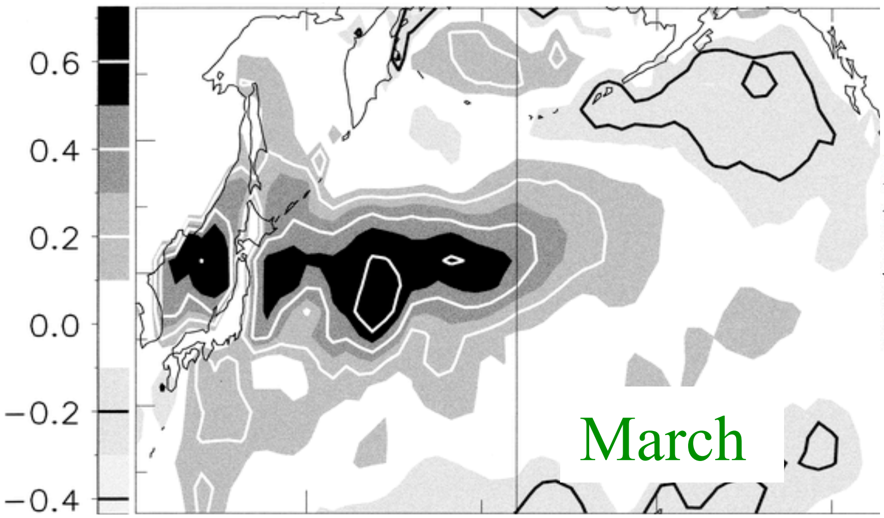
Wind Generated Rossby Waves



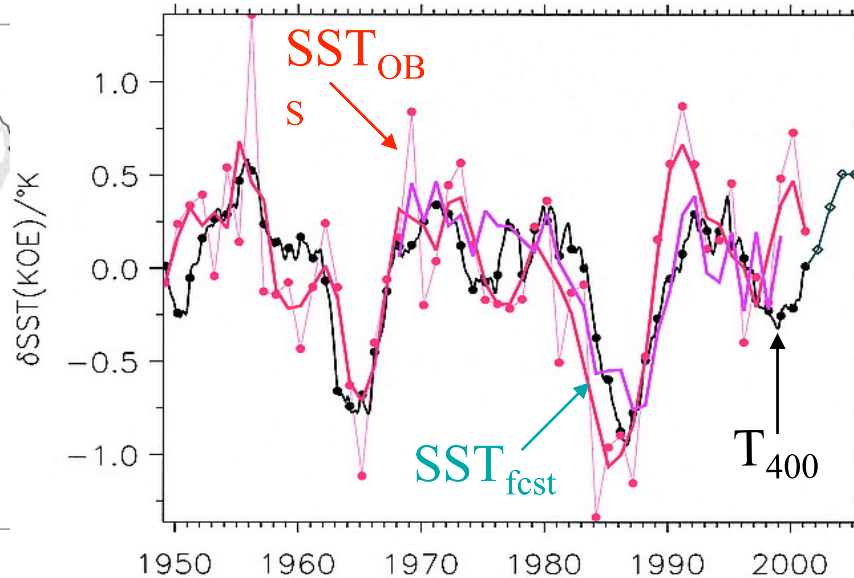
1) After waves pass ocean currents adjust
2) Waves change thermocline depth, if mixed layer reaches that depth, cold water can be mixed to the surface

Observed Rossby Waves & SST

Correlation Obs SST hindcast
With thermocline depth anomaly



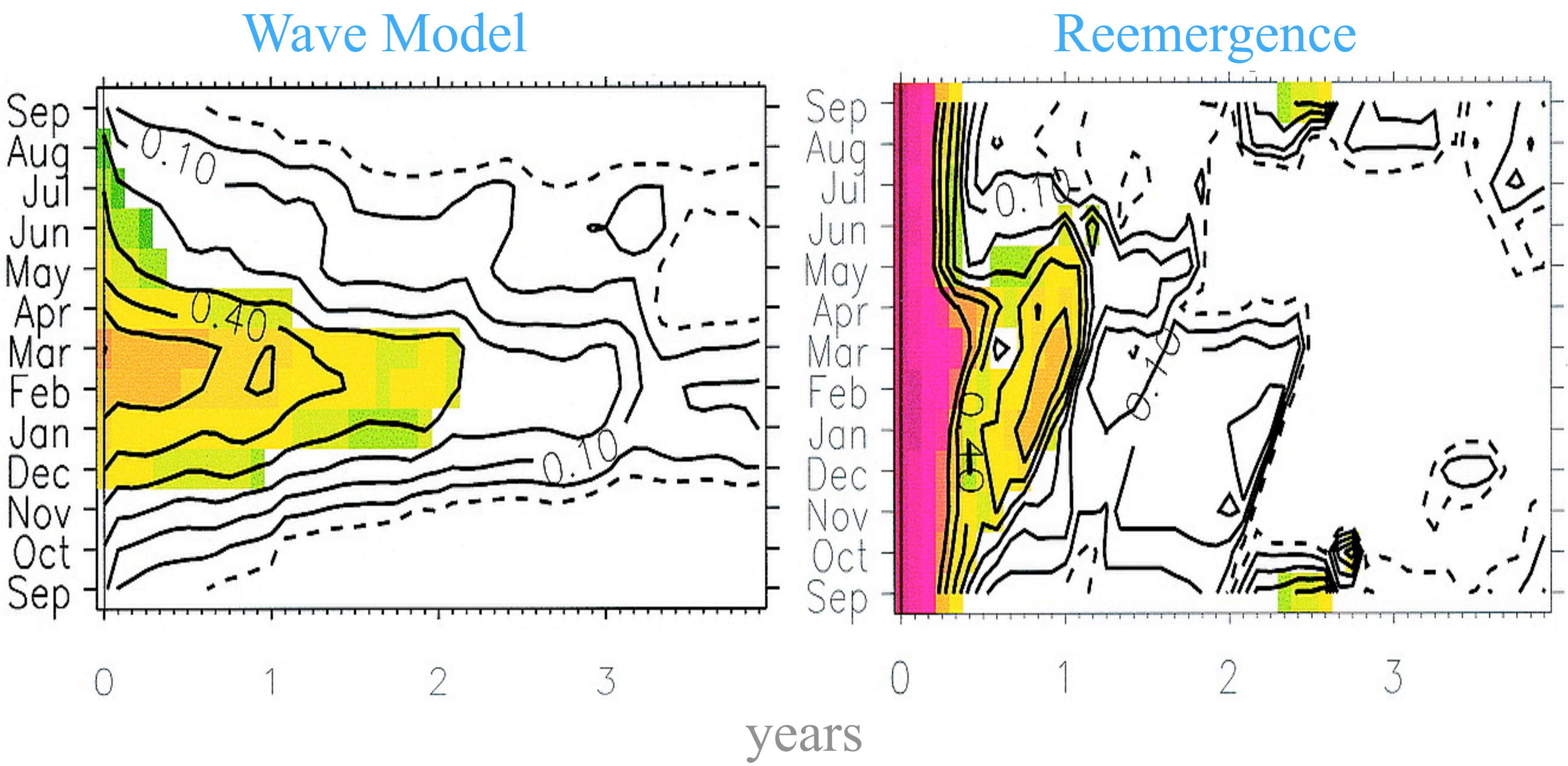
KE Region: 40°N, 140°-170°E



Forecast equation for SST based on integrating wind stress (curl) forcing and constant propagation speed of the (1st Baroclinic) Rossby wave

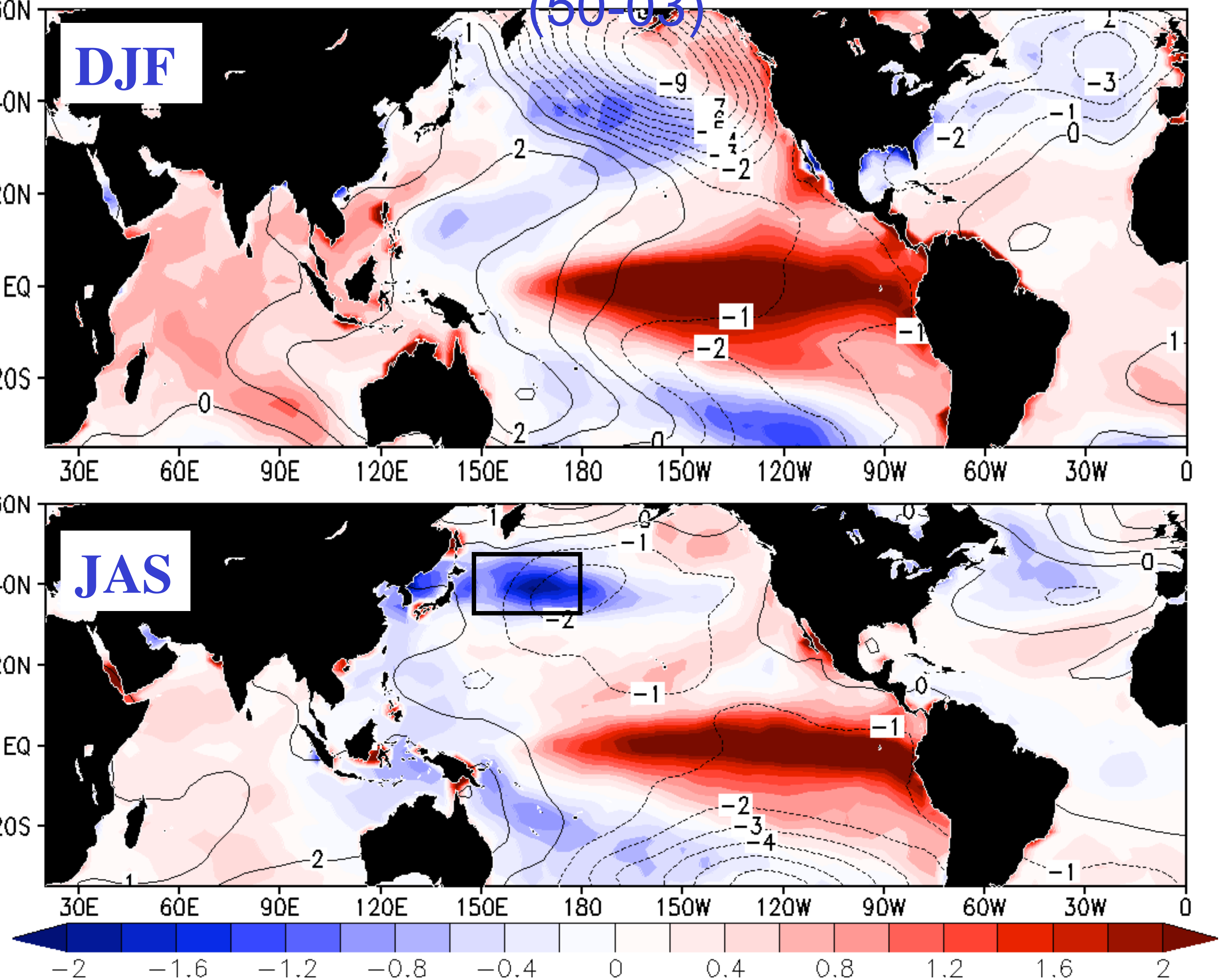
Schneider and Miller 2001 (J. Climate)

Forecast Skill: Correlation with Obs
SST Wave Model & Reemergence

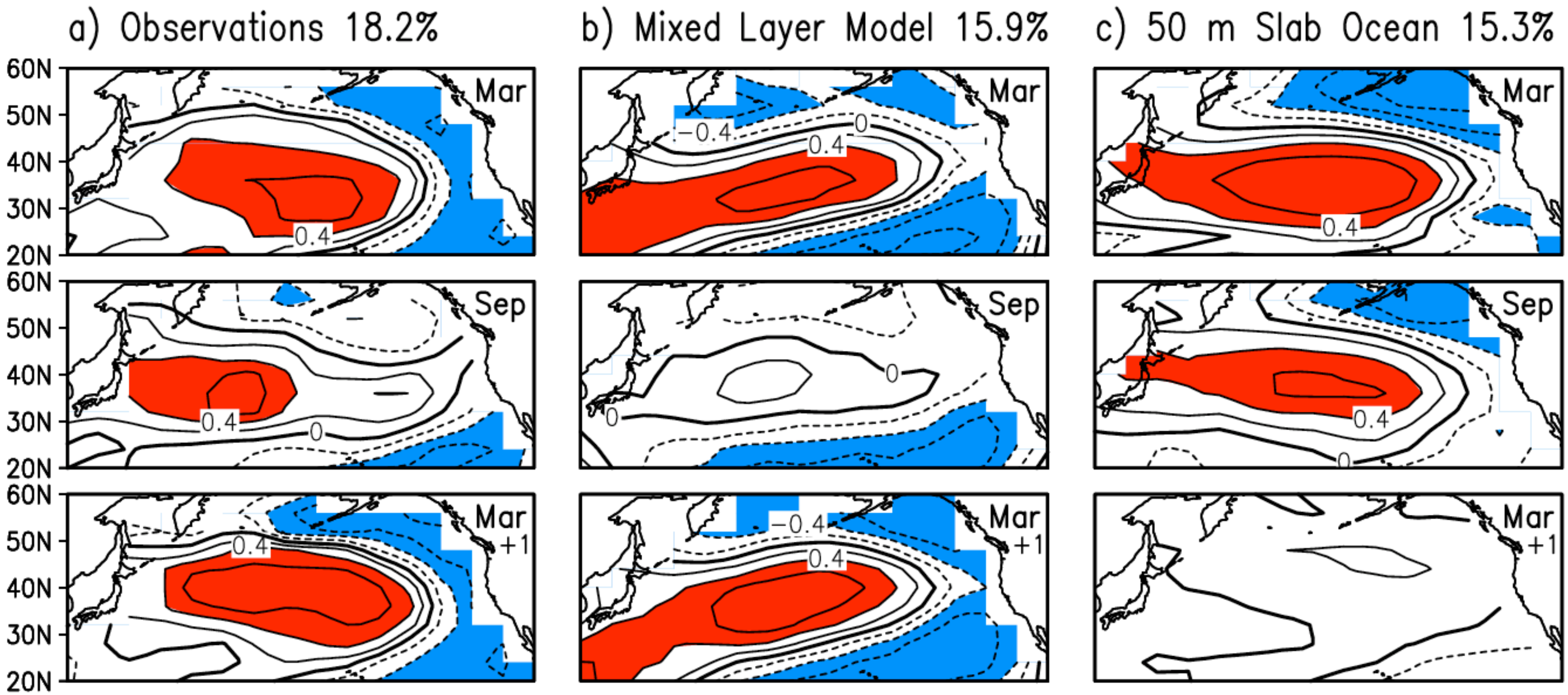


Schneider and Miller 2001 (J. Climate)

Observed SST (°C) / SLP (mb) Warm-Cold (50-03)



Evolution of the leading pattern of SST variability as indicated by extended EOF analyses



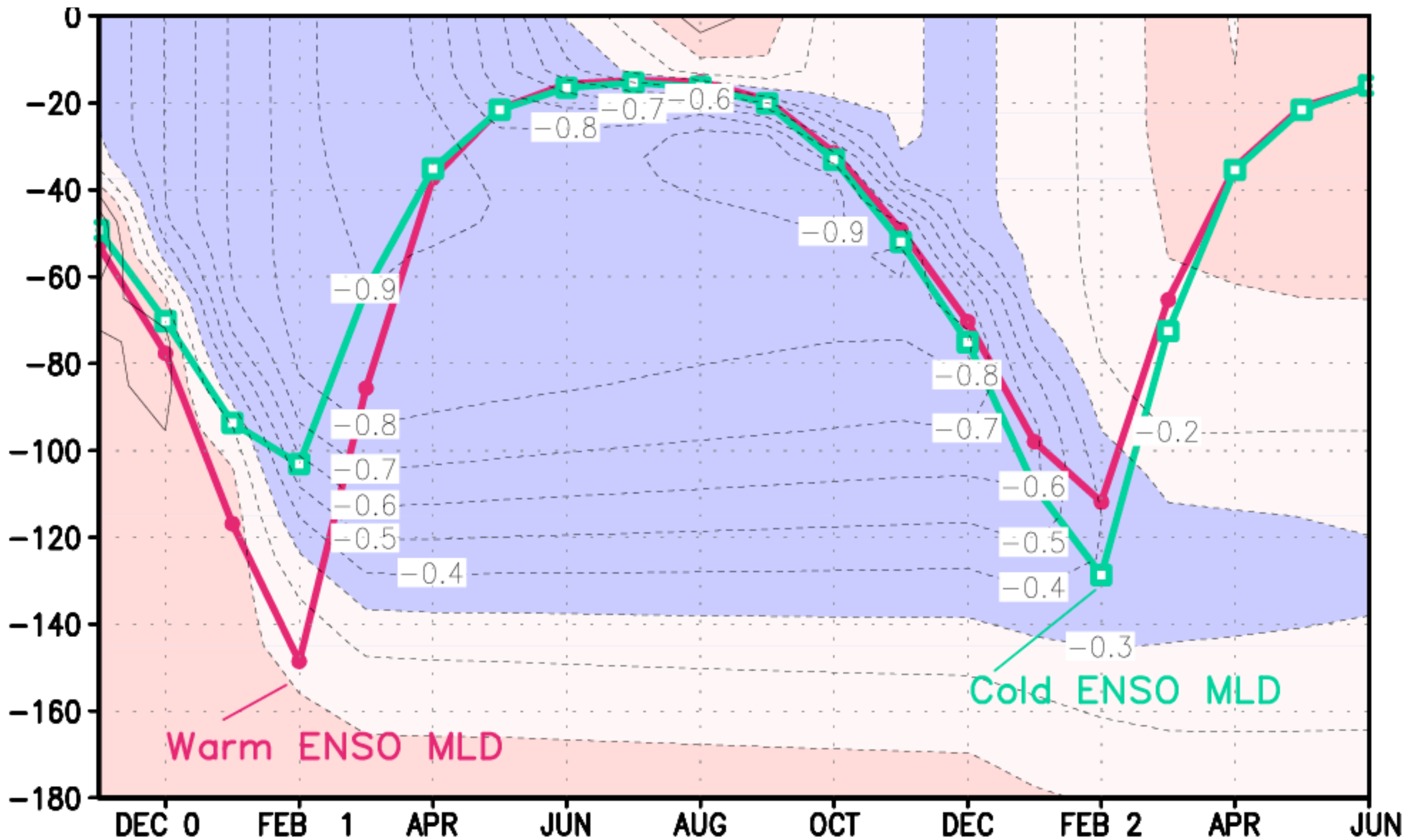
No ENSO;
Reemergence

ENSO;
No Reemergence

Alexander et al. 2001, Prog. Ocean.

Upper Ocean: Temperature and mixed layer depth

El Niño – La Niña model composite: Central North Pacific



Alexander et al. 2002, J. Climate

ENSO SST & MLD in Western N. Pacific Region

Niño – Niña: NCEP Ocean Temp & White MLD (1980-2001)