# COUPLED OCEAN-ATMOSPHERE 4DVAR

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# Coupled Ocean-Atmos 4DVAR: motivation

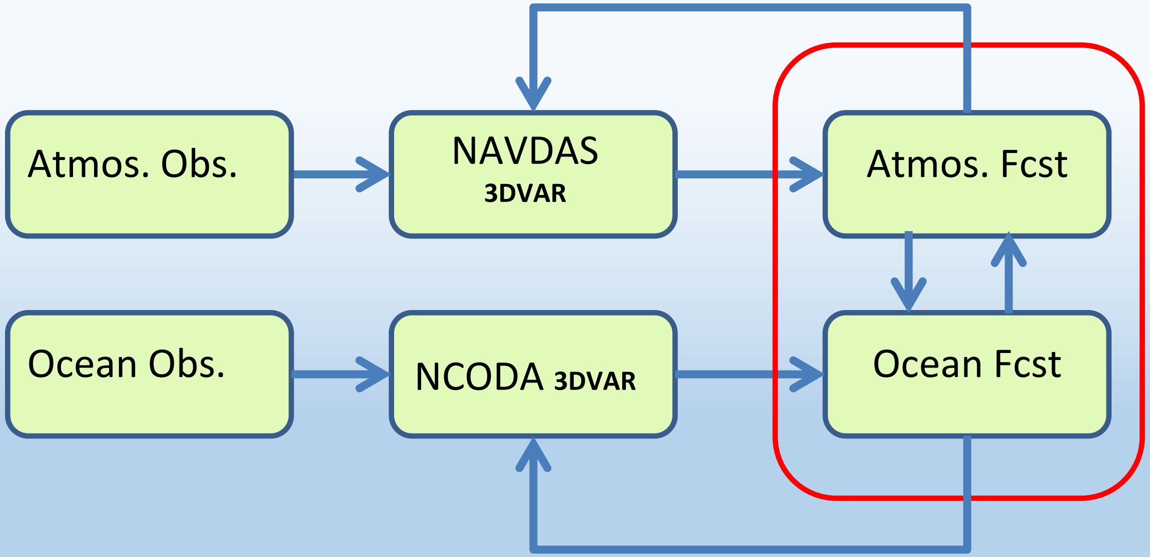
On-going efforts at the US Naval Research Laboratory (NRL) have led  the implementation of the Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS-5): atmosphere-wave-ocean

The analyses in COAMPS-5 are produced from separate 3DVAR based DA systems

Problem 1, separate analyses: the assimilation in one fluid does not take into account the observations or lack thereof in the adjacent fluid

Problem 2:  the absence of a cross-covariance between the fluids prevents the corrections in one fluid from propagating into the other.

This results in unbalanced analyzes and  initialization shocks.



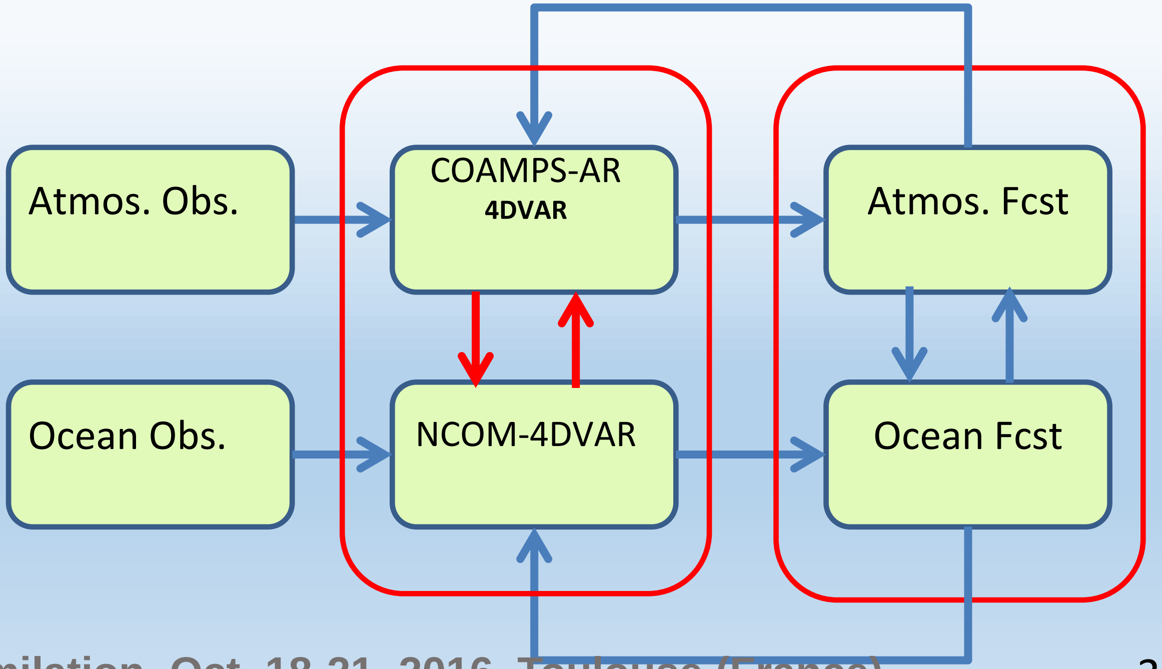
# Coupled Ocean-Atmos 4DVAR

**What is needed is a fully coupled and dynamically balanced analysis.**

**In the meantime, NRL has also developed individual 4dvar systems for the atmosphere and ocean models.**

**This study aims to coupled those 4dvar systems. The new coupled assimilation system will**

1. ***Provide a fully balanced (dynamically consistent) analysis that accounts for all combined observations in both fluids.***
2. ***Reduce the errors in the state estimation and the forecast.***
3. ***Exploit the cross-covariance between the two fluids to provide corrections from observations in one fluid to the other***



# Coupled Ocean-Atmos 4DVAR

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$$u=\begin{pmatrix}u^a\\u^o\end{pmatrix},\quad F=\begin{pmatrix}F^a\left(u^a,i^o\right)\\F^o\left(u^o,i^a\right)\end{pmatrix}$$

Ocean input to atmosphere (bottom boundary condition) : SST
Impact: latent & sensible heat fluxes, temperature, moisture, winds (boundary layer)

Atmosphere input to ocean (surface boundary conditions) : pressure, heat flux, wind stress, precipitation
Impact: circulation, temperature (mixed layer depth), salinity, eddies, waves …

$$C=\begin{bmatrix}C^a & 0\\0 & C^o\end{bmatrix}$$

$$y=\begin{pmatrix}y^a\\y^o\end{pmatrix},\quad H=\begin{pmatrix}H^a\\H^o\end{pmatrix},\quad R=\begin{bmatrix}R^a & 0\\0 & R^o\end{bmatrix}$$

**Analysis/update equation**

$$\hat{u}=u^b+BH^T\left(HBH^T+R\right)^{-1}\left(y-Hu^b\right)=u^b+LCL^TH^T\left(HLCL^TH^T+R\right)^{-1}\left(y-Hu^b\right)$$

$$B=\begin{bmatrix}B^a & B^{oa}\\B^{oa} & B^o\end{bmatrix}$$

***The action of the fully coupled tangent linear and adjoint models provides the cross correlations that are needed to propagate information from the observation in one fluid to the other***

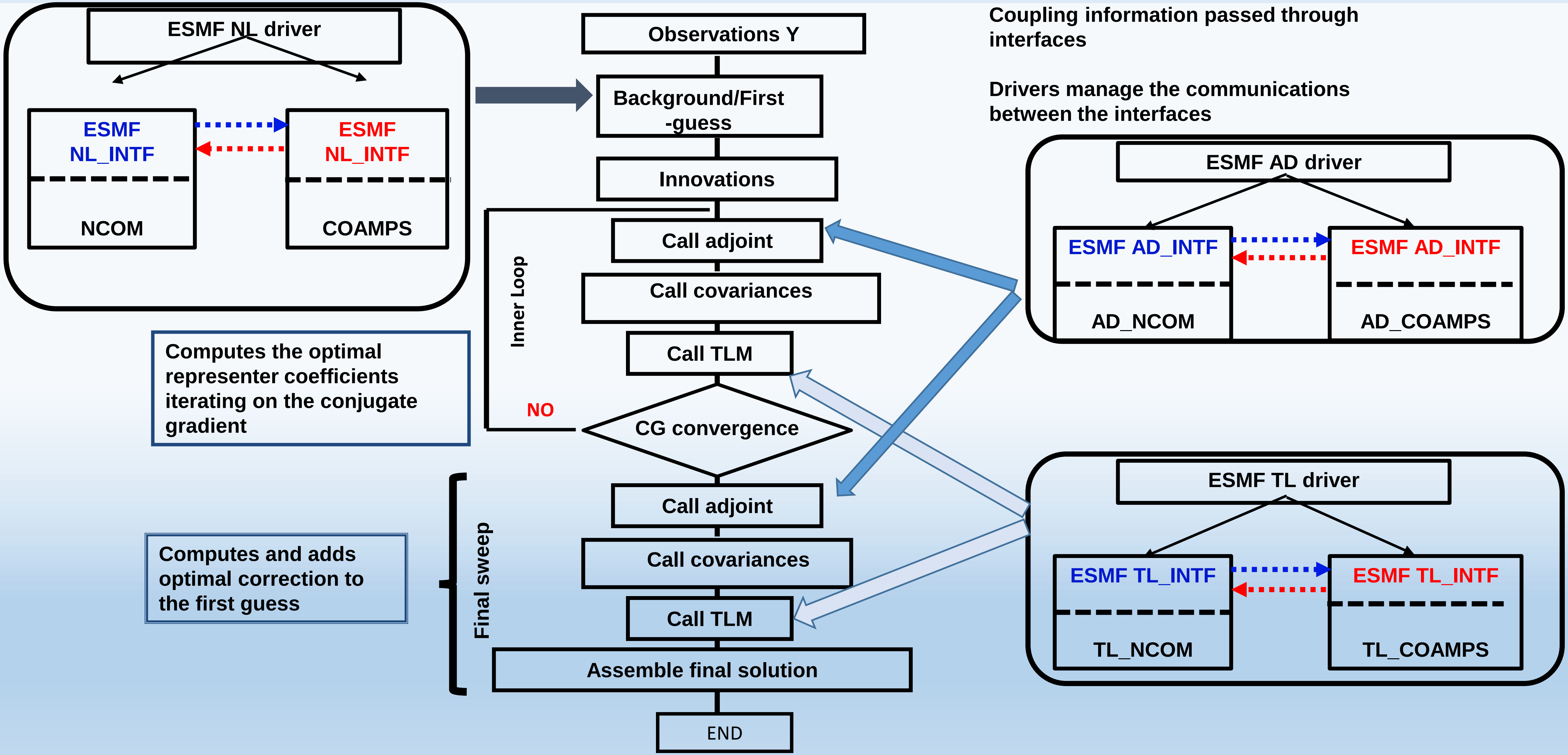
$$L=\left[\frac{\partial F}{\partial u}(u)\right]$$

**Linearization of atmospheric and ocean models, and all nonlinear air-sea fluxes exchange (coupling terms)**

# Coupled Ocean-Atmos 4DVAR

Coupling information passed through interfaces

Drivers manage the communications between the interfaces



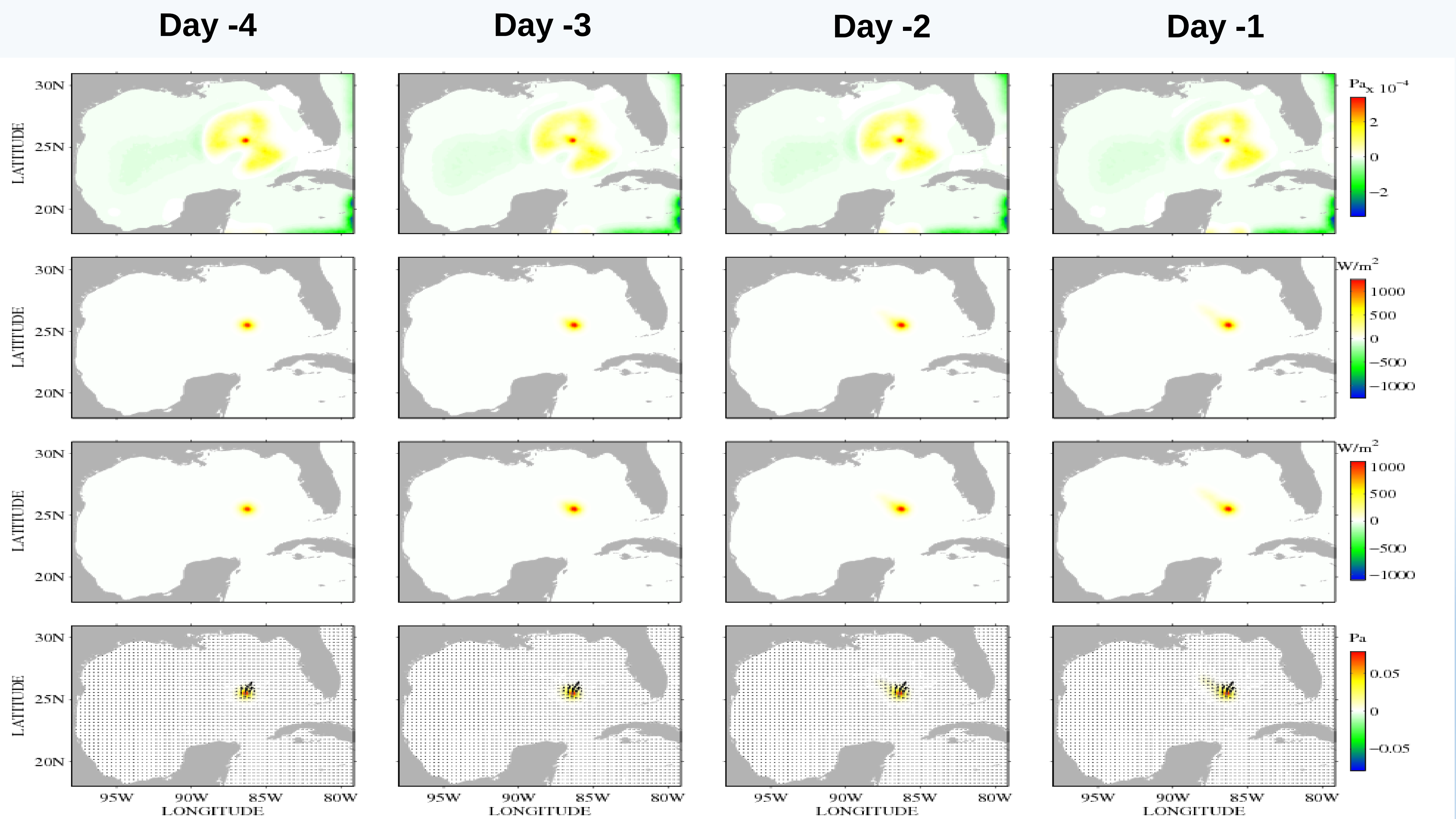
# Coupled Ocean-Atmos 4DVAR: **sensitivity to SST**

**To Atmos. Pressure**

**To Solar Radiation**

**To Heat Flux**

**To Wind Stress**



# Coupled Ocean-Atmos 4DVAR: **sensitivity to surface velocity**

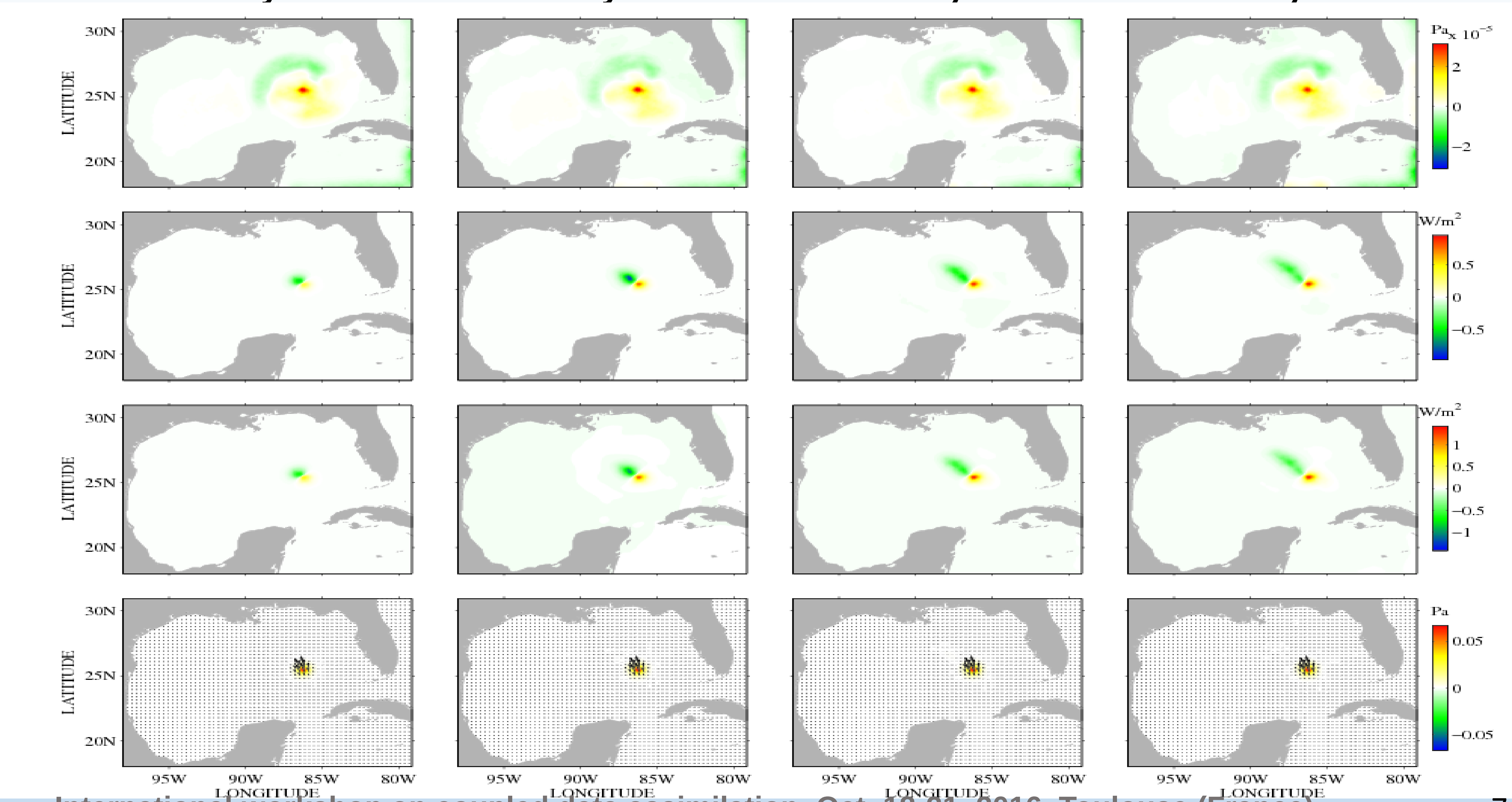
| | Day -4 | Day -3 | Day -2 | Day -1 |
|---|---|---|---|---|

**To Atmos. Pressure**

**To Solar Radiation**

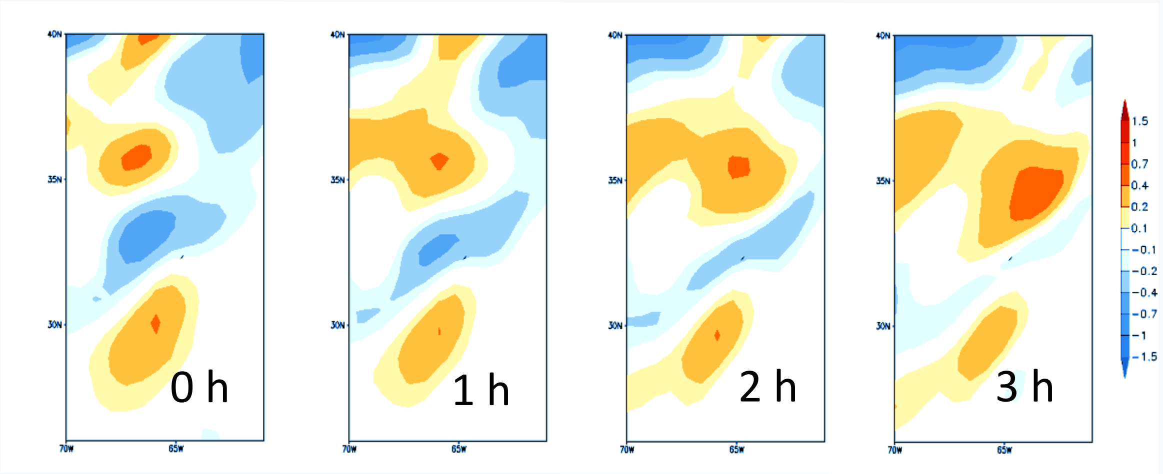
**To Heat Flux**

**To Wind Stress**

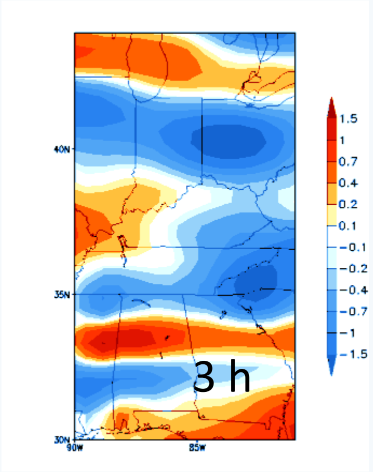


# Why a coupled TLM/ADJ?

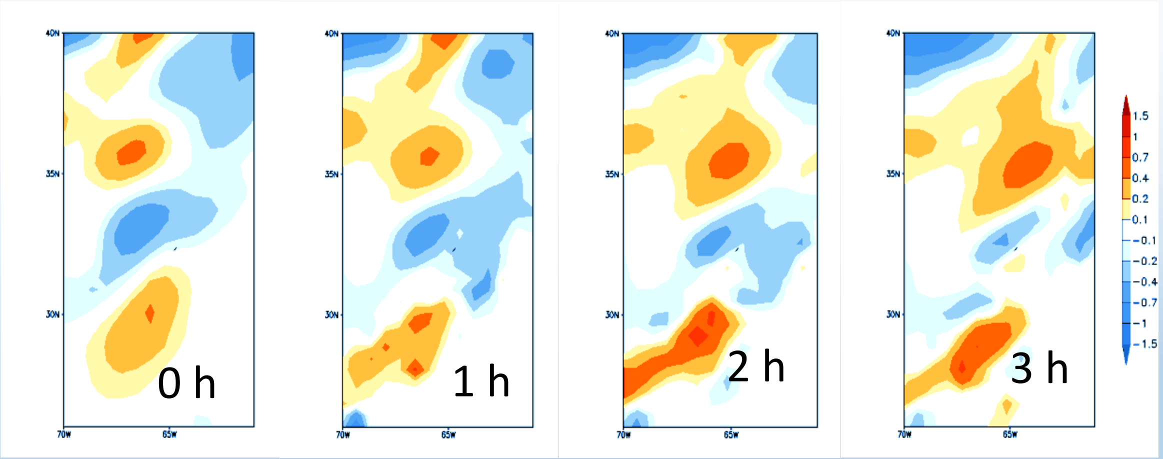
**Analysis increment evolution of *T* by TLM (z=10m)**



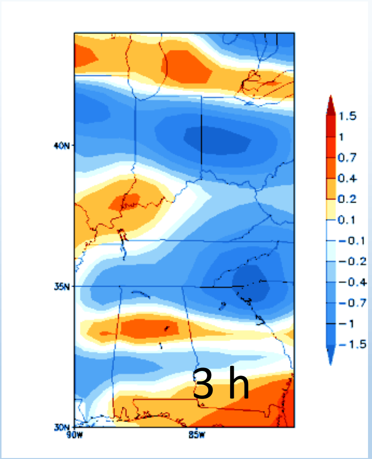

**(z=10000m)**




**Analysis increment evolution of *T* by NLM (z=10m)**

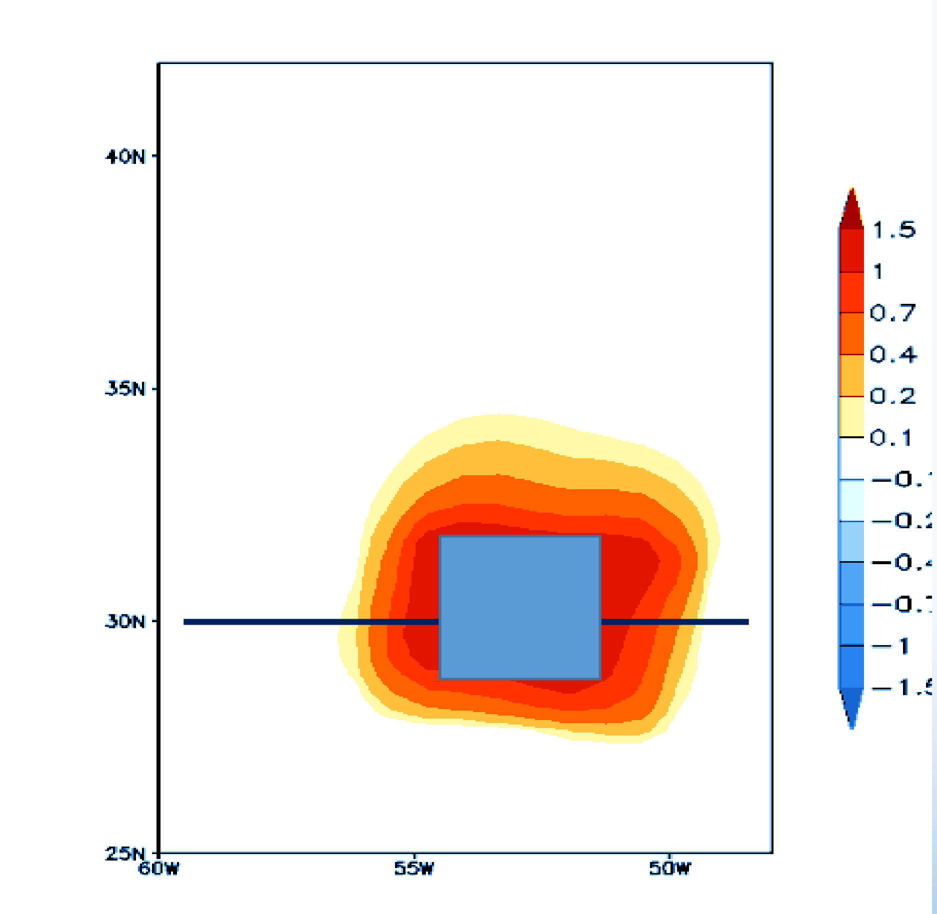



**(z=10000m)**

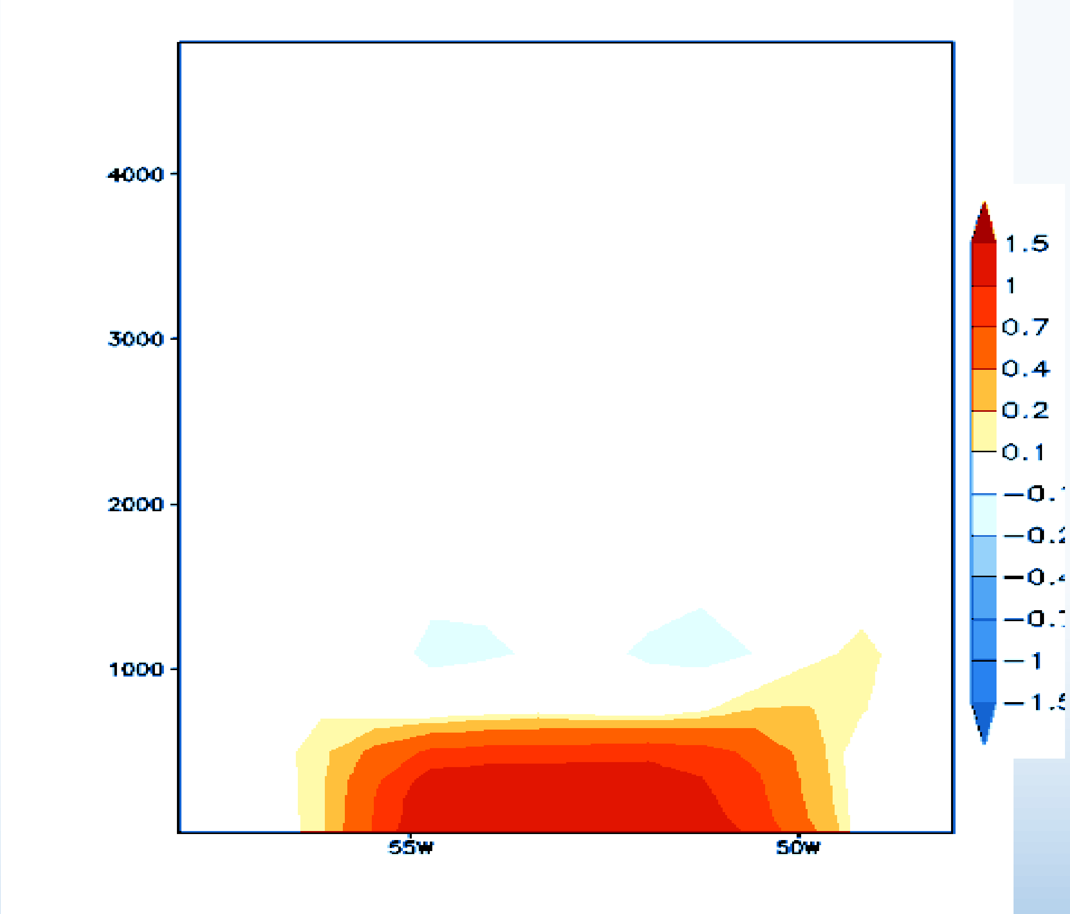



The increment evolution by the TLM does not match the NLM well near the sea surface because the atmosphere doesn't "see" changes to the ocean during the assimilation process

# Coupled TLM




6 h evolution of atmospheric TLM *T* forced only by the upper level ocean in the box indicated in the figure (all initial atmospheric fields are 0)



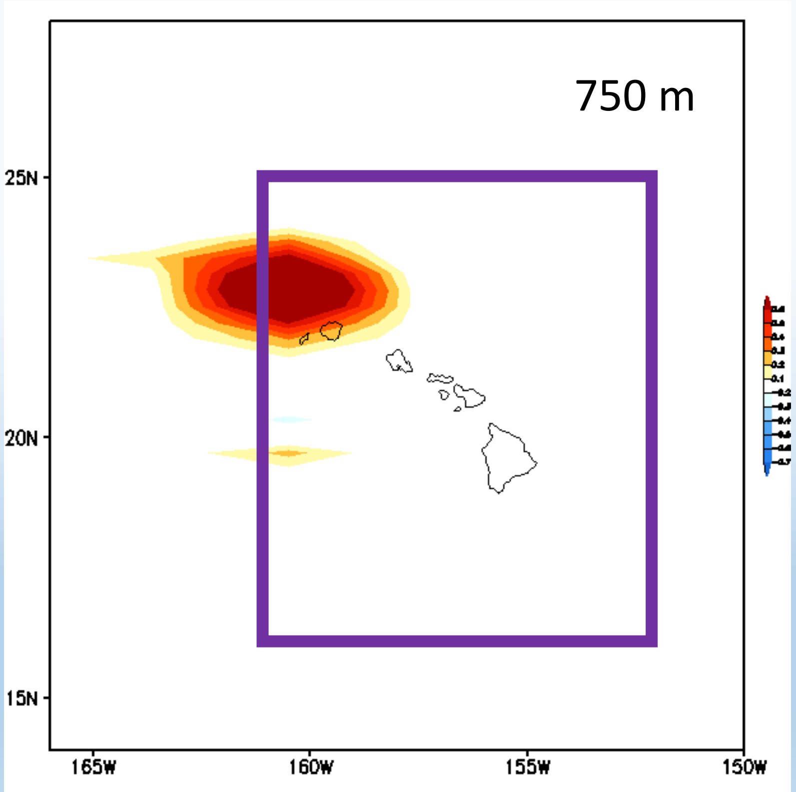

Cross section indicated by the line in the above figure. The atmospheric response is confined to the boundary layer

# Coupled TLM

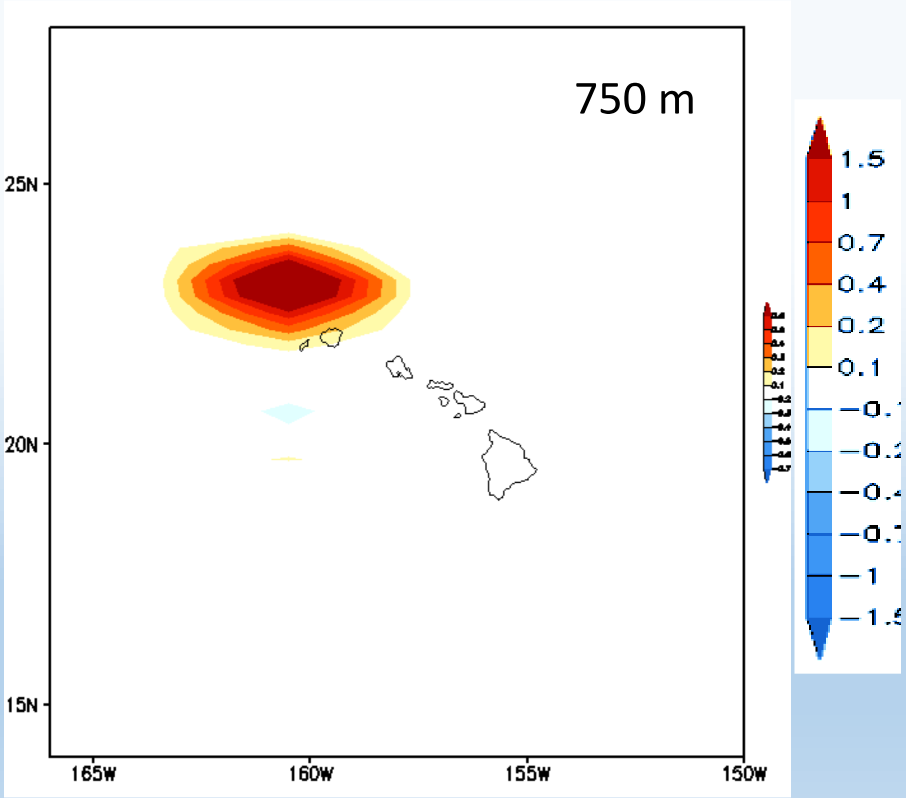
**Atmospheric response to a 1 K perturbation of the top level ocean temp over whole ocean domain (purple box)**

**9 h forecast, ocean is perturbed at initial time, no other perturbations**

Difference in NLM forecasts




TLM forecast



# Coupled adjoint

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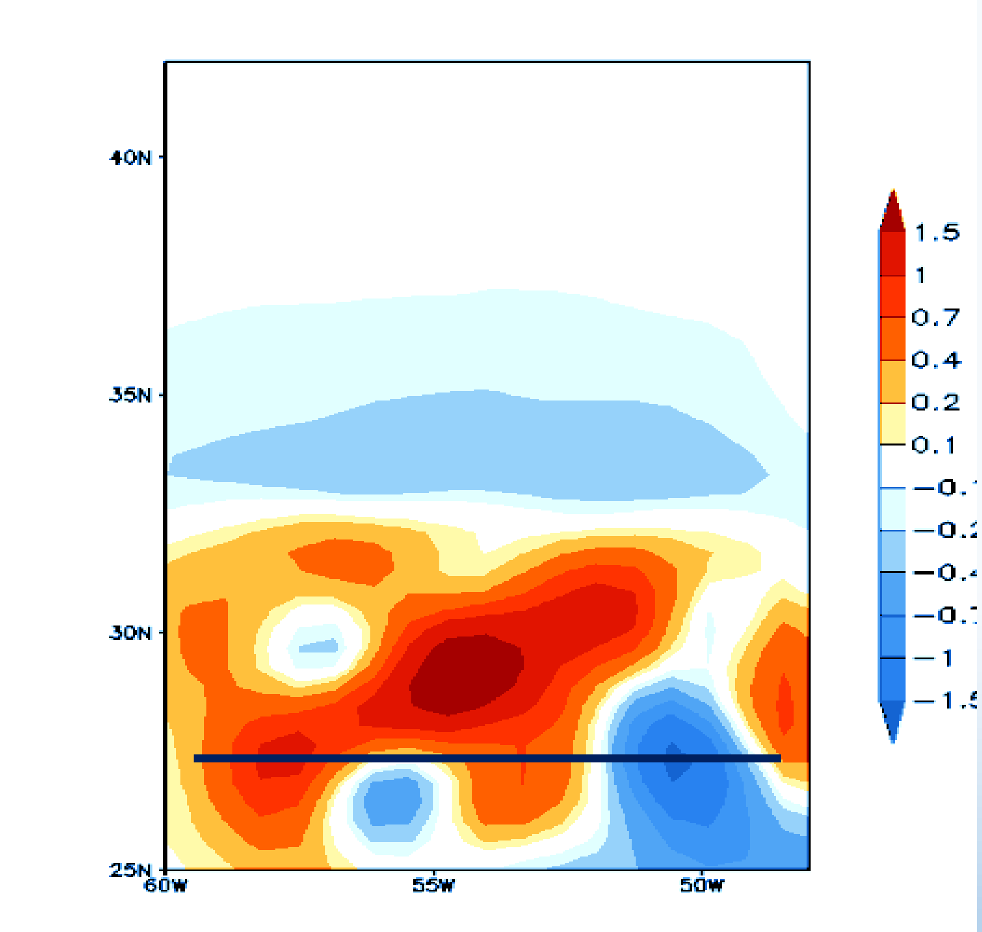
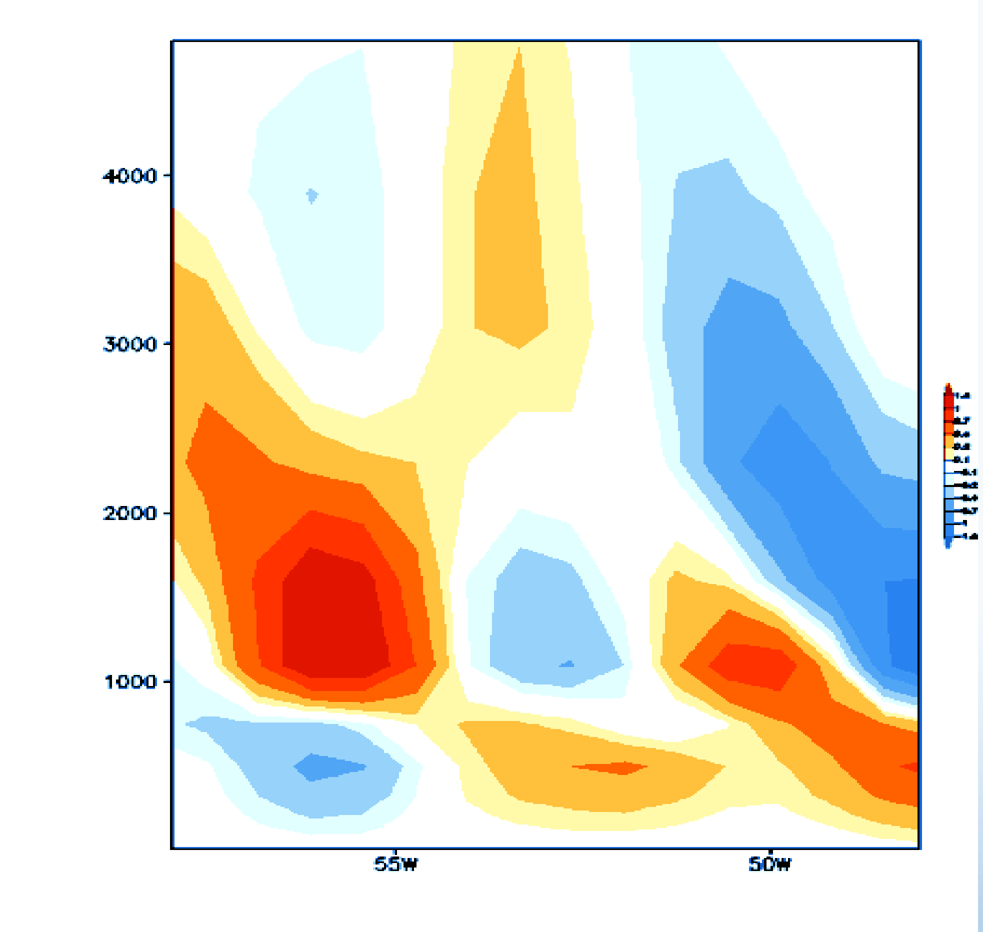


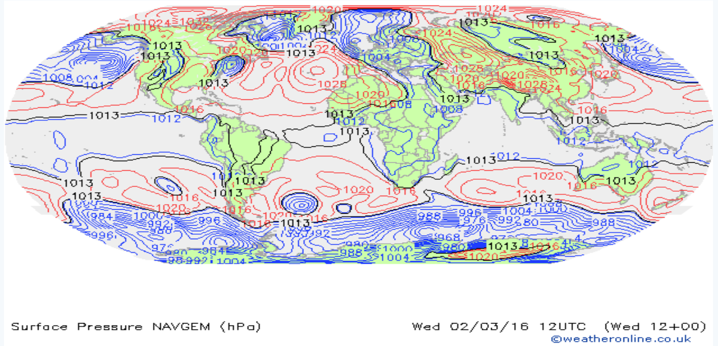

6 h sensitivity of atmospheric winds at 2000 m to the upper level ocean temperature (all initial atmospheric adjoint fields were 0)

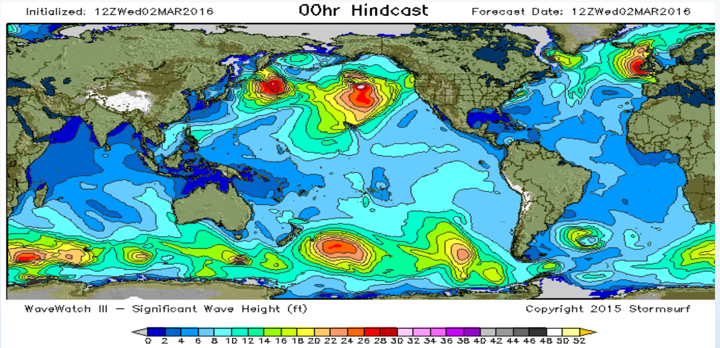


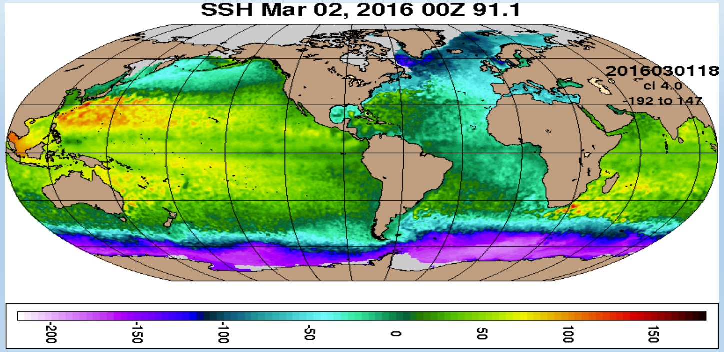

Cross section of sensitivity indicated by line in above figure. Greatest sensitivity is above boundary layer.

# Future plans

- A fully coupled global Atmos-Waves-Ocean-Acoustics 4DVAR system
  - Improves accuracy of initialization of coupled system
  - Bring the benefits of 4DVAR to the global model
    - Minimize the effect of erroneous BCs when forecasting the regional model
- What needs to be done to get there
  - Global Atmos 4DVAR already exists
  - New developments
    - Global ocean 4dvar
    - Global wave 4dvar
  - Leverage existing coupling infrastructure



# Global ocean/waves 4dvar

**Global ocean 4DVAR**

- First, ensure that NCOM-4DVAR can be used for global analysis
- Global HYCOM provides the forecast

$$\hat{u}(x,t) = u_F(x,t) + \sum_{m=1}^{M} \hat{\beta}_m r_m(x,t)$$

- The same forecast is taken as the background for NCOM-TLM
- Use NCOM TLM and adjoint for computing the correction

**Global waves 4DVAR**

- Develop a 4DVAR system for WaveWatch 3 in the same way that SWAN-FAR was developed
  - WW3 TLM and adjoint
  - ESMF interfaces

# Conclusion

- Work is underway in developing a fully/strongly coupled atmosphere-ocean 4dvar system
- Preliminary results of coupled TLM and coupled adjoint show the ability to propagate the information properly across the fluids
- The system will be tested for regional applications first
- Future plans include the expansion to global applications that also include waves coupling
- That will require the development of global 4dvar for both ocean and waves models