The Gulf Stream, the Jet Stream and ... the "Quantum Café"*

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Abstract

This notes addresses the issue of robustness of the Jet Stream response to changes in the state of the Gulf Stream. It is suggested that as long as the oceanic forcing is controlled by eddy mean flow interaction at upper levels of the troposphere, details of the associated change in sea surface temperature and background atmospheric flow will matter to predict the climatic impact of the Gulf Stream variability. A different type of oceanic forcing is associated with the organisation of mesoscale atmospheric convection by the Gulf Stream, but this pathway is fundamentally stochastic in character.

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*Notes for the US-CLIVAR "Whither the Gulf Stream workshop" held at WHOI in June 2022.

1 Motivation: the "Quantum Café"

In a TV series about Quantum Mechanics, the physicist Brian Greene enters the "Quantum Café", where the world is a bit weird and, after asking if he can get an orange juice, receives as a response: "I'll try"[1] . Sometimes, reading about, and comparing the responses of Atmospheric General Circulation Models (AGCMs) to prescribed sea surface temperature (SST) anomaly feels a bit like entering the "Quantum Café"... Different models forced with the same SST anomaly predict a very different response (e.g., [30]; [21]), or the same model forced with the same SST anomaly but at a slightly different time in winter (November and January) likewise produces completely different responses ([23]), or the same model and the same SST anomaly but, in one case a magnitude of $3.6K$ and in the other a magnitude of $0.04K$ (i.e. 81 times weaker), yields the same response ([28], compare their Fig. 4a and 4i). I could go on.

It is given that the atmosphere is chaotic but here these different responses arise even after averaging over many realisations and/or over long time periods. Thus the sensitivity discussed in the previous paragraph applies not just to a single realisation, but to the ensemble average. For example if an ensemble of N experiments has been carried out and one is interested in the surface pressure field p_s at a location $\boldsymbol{r}$ and a time t after an SST anomaly

[1] See `https://www.youtube.com/watch?v=t2CGXRcVFwE`

has been imposed, the sensitivity applies to:

$$< p_s(\boldsymbol{r}, t) > \equiv \frac{1}{N} \sum_{n=1}^{n=N} p_{s,n}(\boldsymbol{r}, t) \tag{1}$$

where the bracket denotes ensemble mean.

It is also the case that the models considered are full state-of-the-art AGCMs or even high resolution regional models, and none have obvious flaws in their formulation – in fact they are as good as it gets in atmospheric modelling. And for each simulation as one goes into the full chain of events establishing the response, one finds that the chain of causality is clear and physically sound (e.g., [25]). These considerations lead me to ask:

- Q1 Is the forcing of changes in the atmospheric Jet Stream by ocean currents such as the Gulf Stream fundamentally a "case-by-case" problem in which details matter?
- Q2 Or are there processes within the coupled ocean-atmosphere system which are missing in the current modelling framework and which, if they were present, would lead to a more linear state of affair?

In this note we will go in and out of the Quantum Café as we look into ocean-atmosphere interactions of spatial scales ranging from a few 10s of km to a few 1000s of km, and timescales of a few weeks to a few years. The focus is on the winter season.

2 Simulated and "observed" responses of the Jet Stream to Gulf Stream shifts

We start by a review of published work on the response of AGCMs to SST anomalies in the North Atlantic. Specifically, we focus on the response to meridional shifts of the Gulf Stream and the so-called SST tripole, which both have significant temperature anomalies in the vicinity of the Gulf Stream. The latter is the upper ocean component of a leading mode of covariability with atmospheric circulation anomalies associated with the North Atlantic Oscillation (NAO) on weekly to interannual timescales ([4]), while the former is the leading mode of Gulf Stream variability, as identified by the position of the $15°C$ isotherm at 200m ([15]). An example of the associated SST anomalies is shown in Fig. 1. Warmer conditions are found to the north and downstream of a poleward shifted Gulf Stream (left panel), with amplitude on the order of $0.4°C$ per std of the Gulf Stream index used by [15] (in the figure the SST lags the Gulf Stream shift by one year). The SST tripole is simply revealed here (right panel) by comparing the SST field in the winter 2014-2015 (positive NAO winter) to that in the winter 2009-2010 (negative NAO winter). A broad patch of warm anomaly in excess of $2°C$ is seen southeast of the separated Gulf Stream, and comparable warm SST anomaly, but with a smaller meridional scale, are also found to the north of the stream in the region of maximum SST gradient (the white lines indicate the averaged SST with a contour interval of $2K$).

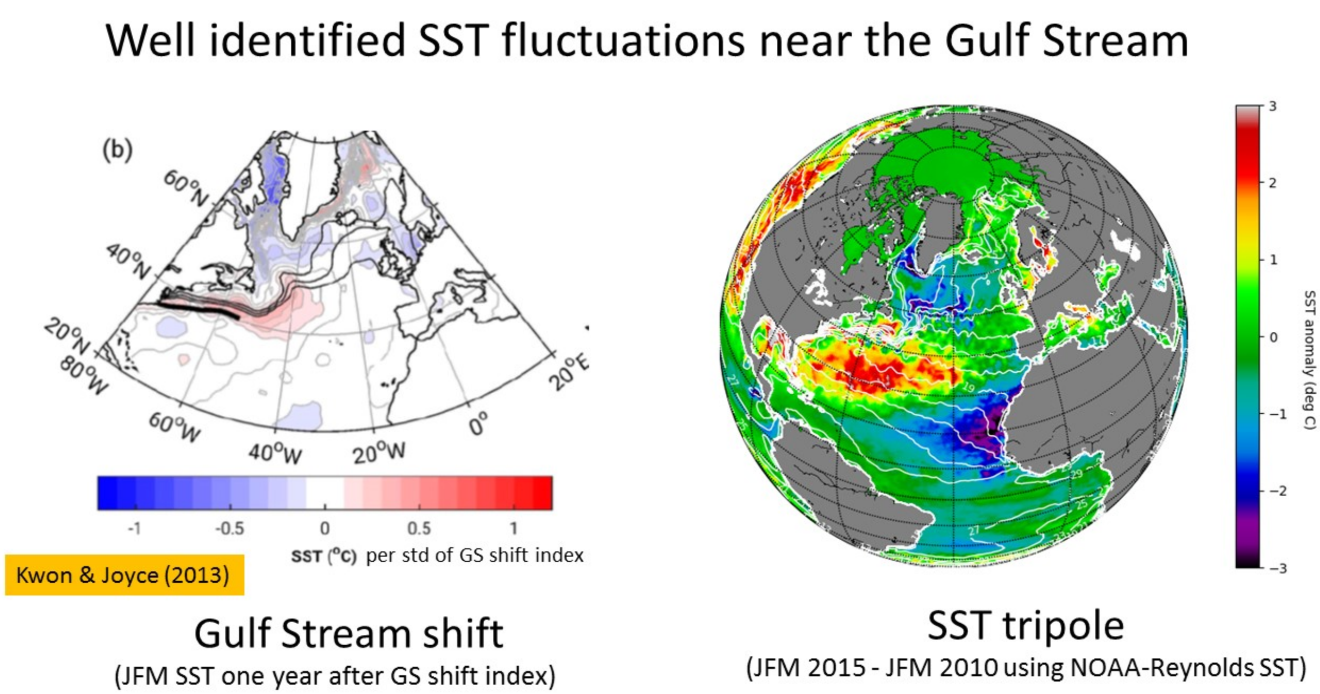

Figure 1: SST anomalies in the vicinity of the Gulf Stream. Both panels refer to SST anomalies taken in January-February-March (JFM). See text for details.

To characterise the response of the atmosphere to these anomalies, the change in SST is displayed in subsequent figures on the x-axis, a positive value indicating warmer conditions near the Gulf Stream. On the y-axis, a measure of the response in surface pressure is given, with the convention that a positive value reflects positive NAO-like anomalies (i.e., anomalously low pressure conditions at high latitudes and anomalously high pressure conditions in midlatitudes). The surface pressure is chosen because most studies have reported the change in this variable. Although it is a surface variable, all circulation anomalies discussed here have a relatively simple vertical structure (intensifying with height), so the Jet Stream is captured by looking simply at the sea surface[2]. A line with slope of $2hPa/K$ is indicated for reference.

We start in Fig. 2 by displaying the results of the large number of experiments conducted by [28] with the WRF model run in a regional configuration and with an horizontal resolution of $40km$ (purple diamonds). It is seen that, for a broad range of magnitude of warming and cooling, possibly reflecting a range of poleward and equatorward shifts of the Gulf Stream, the AGCM responses all fall approximately along the same values of $\approx -1.5hPa$. Thus a small or large poleward shift of the Gulf Stream causes in this model blocked atmospheric conditions in high latitudes and tends to suppress the Jet Stream there. But, strikingly, a similar response is found if the Gulf Stream shifts equatorward.

It is difficult to establish straightforwardly an observational counterpart to these experiments. One approach is to look at lead-lag covariances between SST and atmospheric variables in reanalysis data ([2]). In the framework of stochastic climate model this allows a quantitative estimate of the circulation anomalies responding to an SST anomaly, although the exact magnitude of this response is difficult to estimate ([7]). Because of these difficulties, and also because the technique is usually applied to reanalysis data and not to direct observations, the results from such studies are labelled here as "observed". This type of estimate is indicated by an open black diamond and two studies are reported. In the first ([8]), analysis of the monthly covariance between a Gulf Stream path obtained from satellite altimetry and geopotential height anomalies from the NCEP-NCAR reanalysis could not find any evidence of oceanic forcing. The values for this study are thus represented with a value of $0hPa$ in Fig. 2. Because the technique used by

[2]Indeed, as discussed by [9] (see his section 13.10), the surface winds can be thought as reflecting the transfer of momentum by meanders developing on the Jet Stream near the tropopause!

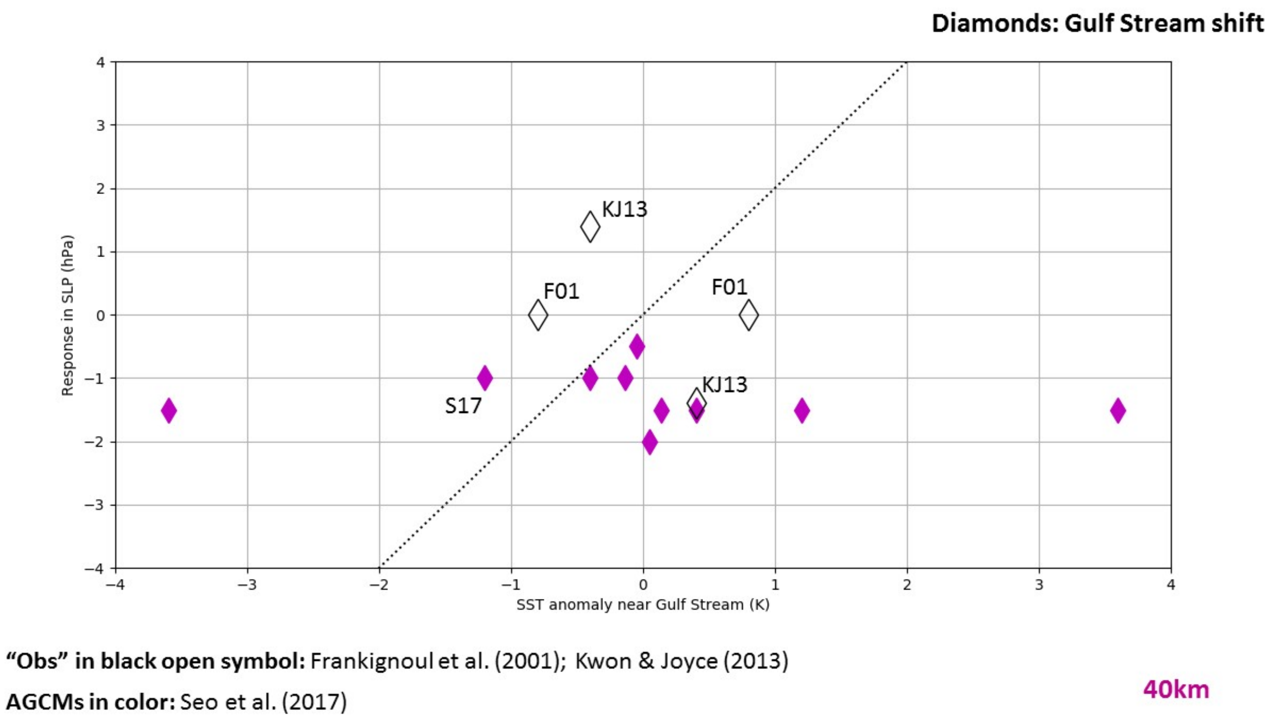

Figure 2: Simulated and "observed" response of the Jet Stream to Gulf Stream shifts. See text for details.

[8] is linear two diamonds are shown, for both the positive and negative SST anomaly associated with one standard deviation of their Gulf Stream path (about $1K$).

A second "observed" estimate of the tropospheric response to Gulf Stream shifts was provided by [16], who used lagged regression between the path of the Gulf Stream, determined from subsurface temperature data, and the MERRA atmospheric dataset. Their finding is plotted in Fig. 2 as two open black diamonds. Unlike [8], [16] argued they coul detect a non zero response. For a poleward shift of the Gulf Stream their regression maps show the presence of blocking conditions at high latitudes, consistent with the results of [28] for moderately warm SST anomaly. However, since the technique used by [16] is linear, an equatorward shift is associated with more westerly flow at high latitudes, which differs from the non linear response dominating the results in [28].

A final set of AGCM estimate of the tropospheric response to a Gulf Stream shift is provided by a recent study ([21]) who compared the response of AGCMs of high (50km or higher) and low resolution (100km or lower) to the imposed time history of global SST anomaly over the 1950-2014 period. By isolating through composite analysis the periods with a northward and a southward displaced region of maximum SST gradient in the western North Atlantic (taken as proxies for years with poleward or equatorward Gulf Stream displacements), they obtained the results reported in Fig. 3 in orange, red and green coloured circles. Strikingly, the high res models (red and orange) produce more westerly flow at high latitudes in response to a poleward shift of the Gulf Stream, while the low res models (green) produce more blocking. Note that the composites shown in [21] are the difference between positive and negative index years. The high res responses agree with the results of [28] for the cold SST anomalies, but not for the warm ones. The reverse is seen for the low res models. A comparison of these results is made with the observational estimate by [32], whose SST index is maximised in the region studied by [21]. Their results, shown by two black open circles for the warm and cold phase, are found to be in good agreement with the low res models, but disagree with the high res models.

We finish this brief overview of modelling and observational studies by considering the tropospheric response to the SST tripole (Fig. 4). The latter was investigated in several studies in the early 00s with AGCMs which are considered quite low resolution by today's standard (horizontal grid spacing $> 200km$, blue coloured squares). Nevertheless, the responses are among the

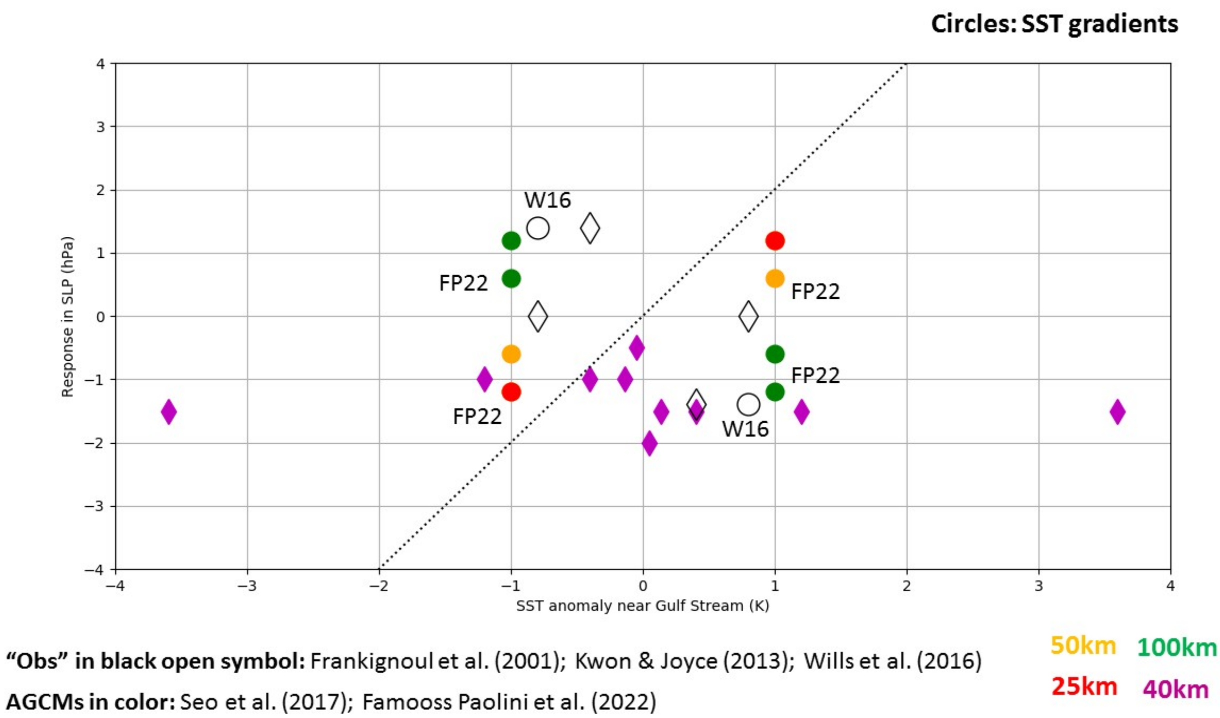

Figure 3: Same as Fig. 2 but with data points added from the study of [21] and [32]. See text for details.

largest seen (compare with Fig. 3) and are also quite consistent between the AGCMs. They are also in agreement with the observational estimate shown by the open black square.

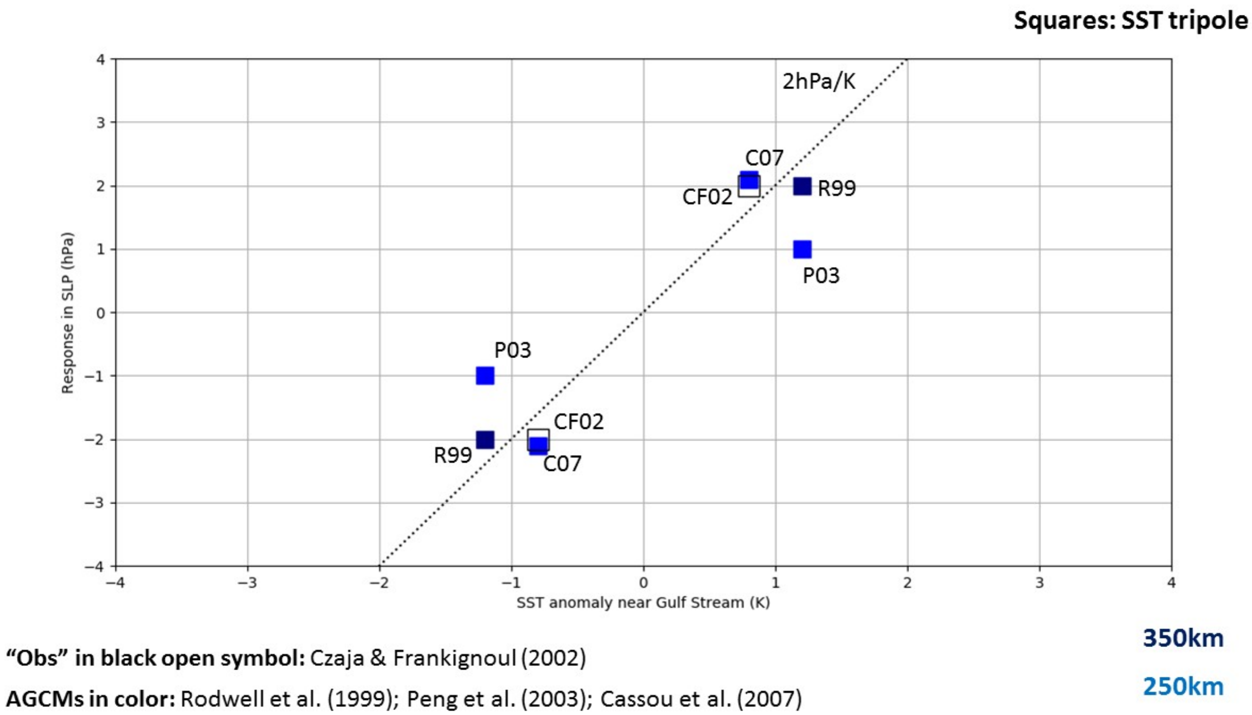

Figure 4: Same as Fig. 2 but for surface pressure anomalies developing in response to the SST tripole. See text for details.

Inspection of Figs. 3 and 4 reinforces the relevance of the questions Q1 and Q2 asked in Section 1. It is clearly seen in Fig. 3 that a poleward displaced Gulf Stream can, in some situations, lead to more blocking at high latitudes but that it can, in some other occasions, lead to more westerly flow there. Conversely, it does seem as though when warm, large scale SST anomalies near the Gulf Stream are flanked by cold, large scale anomalies poleward and equatorward, as does happen with the SST tripole, there is a more robust response of the AGCMs (Fig. 4). It is likely that a detailed analysis of these models would reveal a sound chain of causality leading from the displaced Gulf Stream to the SST anomaly and associated anomalous diabatic heating in the troposphere, and from there to the shift in the Jet Stream. So what is really going on here? Why such different behaviours?

3 A framework to understand the root cause of Quantum Café behaviour

From the point of the view of the storm-track / Jet Stream system, the presence of an SST anomaly generates a perturbation to the flow and the impact of the latter on the fluxes of heat and momentum by synoptic weather systems is very sensitive to the total (background + SST induced) flow. A beautiful demonstration of this effect was provided by [26] in their study of the response of the North Pacific Jet Stream to a large scale SST anomaly in that basin, and this is illustrated in Fig. 5. The SST anomaly pattern is shown in the top right portion of the figure, reaching a maximum of about $2.5K$, and it was imposed in a perpetual January or February state of the National Center for Environmental Prediction AGCM (18 levels, T40, i.e. approximately $3°$ resolution). A linearised version of the model around each month's background state shows that the initial response of the AGCM to the SST anomaly is quite similar between the two cases (middle left panels). In each, an anticyclone is seen to develop over the basin with an amplitude of about $35m$ in the geopotential height field at $250hPa$. The change in eddy momentum fluxes induced by this anticyclone, estimated using a linear storm track model discussed further below, are however completely different in January or February. As seen in the bottom right panels, in January the effect of the eddies, represented here in terms of geopotential heigh tendency, is to shift the anticyclone to the North East, while it reinforces it in February. The ensemble mean equilibrium response for February is, consistent with this eddy forcing at upper level, an equivalent barotropic ridge. In January however, the lack of eddy reinforcement leads the AGCM to develop a baroclinic response, with a low surface pressure downstream of the warm SST anomaly.

The linear storm track model was introduced by [31] and takes the view that band-pass eddy statistics reflect an approximate balance between the transient growth and decay of the Jet Stream meanders, and the constant excitation of these meanders by "noise". Mathematically this can be sum-

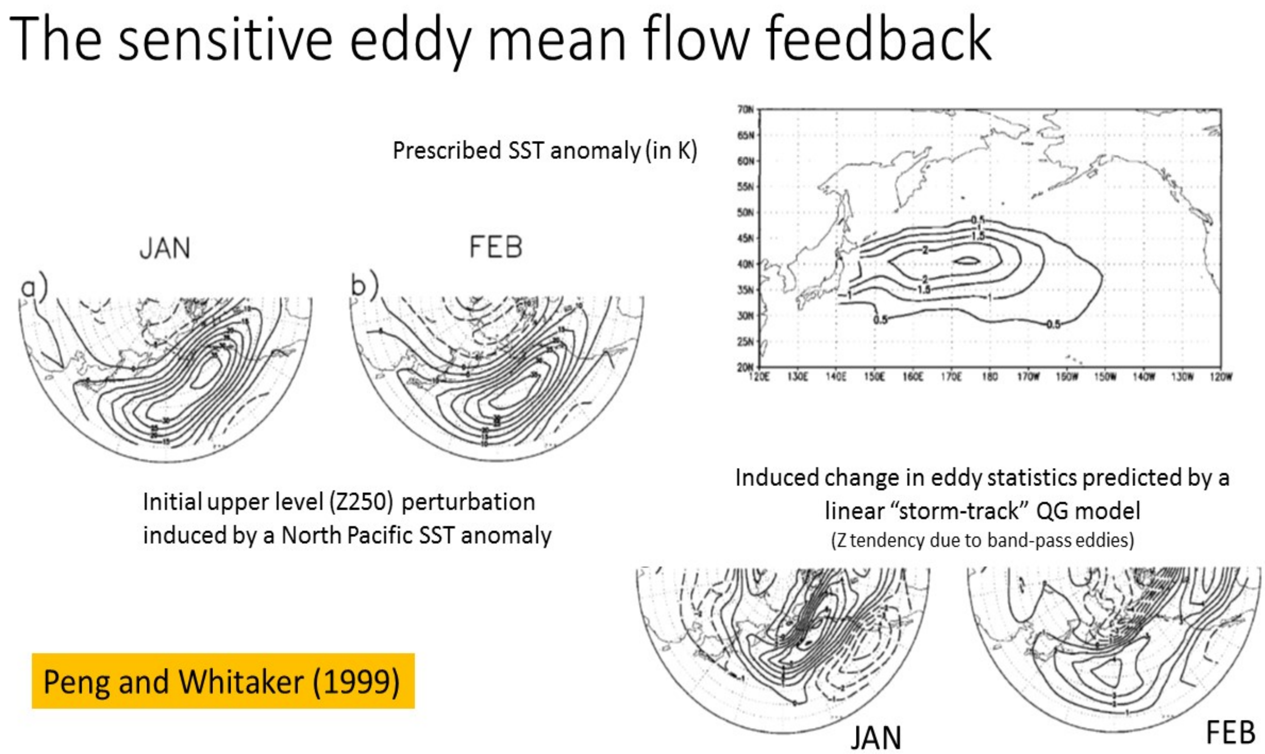

Figure 5: [26] deconstructing the root cause of the Quantum Café behaviour using a linear baroclinic model and a linear storm track model. See text for details.

marised by:

$$(\boldsymbol{L} + \boldsymbol{D})\boldsymbol{C_o} + \boldsymbol{C_o}(\boldsymbol{L}^T + \boldsymbol{D}^T) + \boldsymbol{F} = 0, \tag{2}$$

where $\boldsymbol{L}$ and $\boldsymbol{D}$ are the linear dynamics and damping operators, respectively, $\boldsymbol{C_o}$ is the autocovariance matrix of the band pass eddies, and $\boldsymbol{F}$ that of the stochastic forcing. The role of the ocean in setting the eddy statistics can then be seen as:

- Providing a major source of damping ($\boldsymbol{D}$) to the baroclinic eddies as colder and warmer than underlying SST air masses are advected over the ocean. Indeed, a typical damping timescale of a couple of days seems sufficient to bring unstable normal modes to neutrality ([11]). This timescale is entirely consistent with that expected from air-sea interaction:

$$\tau_{air-sea} = \frac{h}{C_E|U|} \sim \frac{1km}{10^{-3} \times 5ms^{-1}} = 2 \text{ days} \tag{3}$$

  where h is the thickness of the marine boundary layer, C_E is an air-sea exchange coefficient (heat or momentum) and $|U|$ is the low level wind speed. Further discussion of this often overlooked role of the ocean is provided in [1].

- Favouring transient growth in preferred location ($\boldsymbol{L}$), such as western boundary currents. Indeed, much emphasis has been put on the role of the Gulf Stream in setting low level regions with large isentropic slopes and diabatic heating, and acting as a source of growth for synoptic eddies ([13]; [19]). The difficulty here is in isolating the enhancement of eddy activity due to the land sea contrast from that due to the SST front associated with the Gulf Stream. The dynamical term $\boldsymbol{L}$ is that which is responsible for setting the deformation of eddies by the mean flow and for setting the sign and magnitude of the eddy mean flow feedback. It is at the root of the Quantun Café behaviour.

- Organising the "noise" ($\boldsymbol{F}$), which, in the quasi-geostrophic framework shown to be relevant thanks to the remarkable results obtained by [31] with a two-layer (dry) quasi-geostrophic model, represents the energy at scales smaller than the atmospheric deformation radius, i.e., scales of a few hundred km or smaller. The results obtained with AGCMs with resolution on the order of $25-50km$, in terms of their response to the presence of small spatial scale in the SST (e.g., [18]; [17]) suggest a strong role for the Gulf Stream there. We come back to this in exploring one possible mechanism for this effect in section 4.

Some of the perplexing results obtained in Section 2 can now be rationalised within the framework of the linear storm track model –eq. (2). The set of experiments analysed by [21] shows a clear difference of behaviour between the low and high res models. It is always possible that resolution controls in part the eddy mean flow feedback simply because by changing the resolution of an AGCM its mean state is affected everywhere, and so will the dynamic operator $\boldsymbol{L}$. Nevertheless, the framework (2) also invites the possibility that the mesoscale forcing $\boldsymbol{F}$ comes into play when analysing the different responses of low and high res model behaviour to SST anomalies. In models of low resolution, there is little scope for the Gulf Stream shift to organise mesoscale activity and influence noise since this activity is not represented at all. These models are thus entirely controlled by the sensitivity of the eddy-mean flow feedback. In the high resolution models however, it is possible that the organisation of mesoscale noise by the Gulf Stream state changes the dynamics, possibly giving more "grip" to the ocean via $\boldsymbol{F}$. This has to be weighted with the fact that this forcing pathway would be fundamentally stochastic in character (see an illustration of this idea in Section 4).

The more robust results obtained for the SST tripole in Section 2 can also be understood from the framework (2). Because the AGCMs studied in Fig. 4 were low resolution, their spread must entirely be controlled by the eddy mean flow feedback. The latter is quite important to the existence of the NAO itself ([5]) but the presence of the positive feedback seen in Fig. 4 (the tripole forces the same NAO that created the tripole in the first place) has in effect neutralised the Quantum café behaviour: the upper level anomalies which develop rapidly in response to the presence of the tripole SST are already very close to uper level NAO circulation anomalies (see for example Fig. 11a in [25]). As a result the eddy mean flow feedback is "locked" into that of the NAO and there is little spread between the AGCMs. [24] pushed the idea even further and suggested that one could predict the response of an AGCM to an SST anomaly based solely on its intrinsic modes of variability. This could lead to the development of very cheap atmospheric (statistical) models which could be coupled to high res and multi-member ocean GCMs. A comparison of these models with the fully hi-res coupled models could then provide a way to isolate the different types of oceanic forcing in the overall coupled model variability.

4 Atmospheric mesoscale and the Gulf Stream

Standard measures of mesoscale activity, such as CAPE or SCAPE, do not show, when mapped in the North Atlantic, obvious maxima or minima in the vicinity of the Gulf Stream (Fig. 6). However, when a more refined measure is considered, taking into account the vertical extent of the convective instability, not just its bulk value, then the signature of the Gulf Stream on these metrics becomes obvious (Fig. 7).

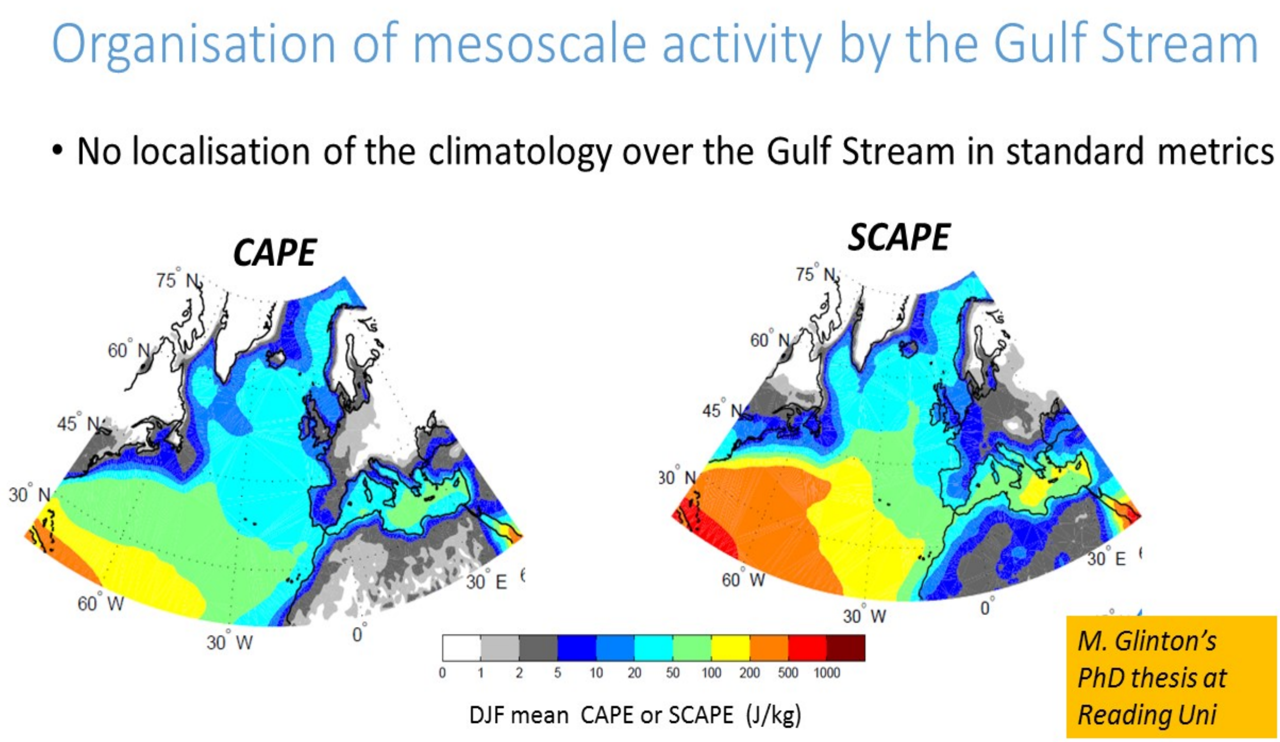

Figure 6: Standard measure of mesoscale activity applied to the North Atlantic. See text for details.

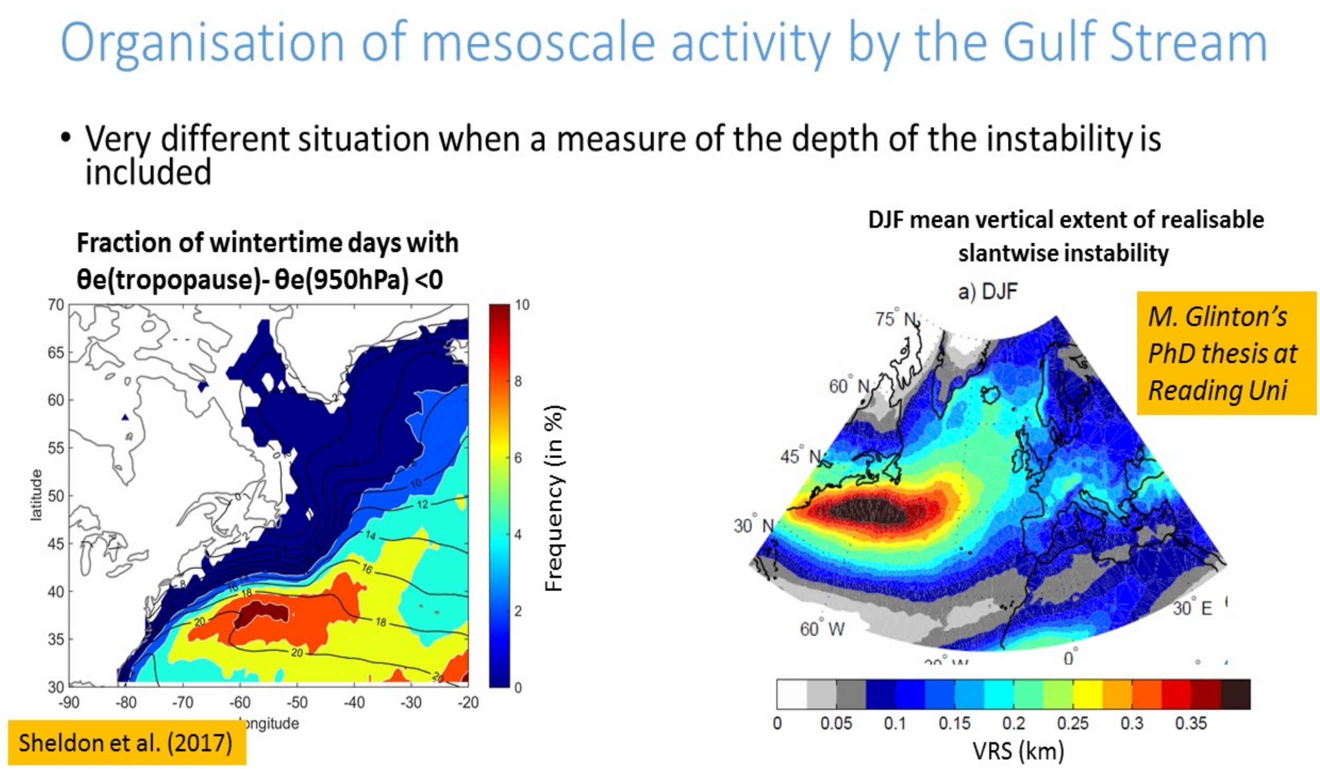

Figure 7: Measures of mesoscale activity including information about the vertical extent of the instability applied to the North Atlantic. See text for details.

This result can be understood from the fact that the distribution of warm waters either centred on the Florida current, or on the equatorward flank of the separated Gulf Stream, tend to be aligned with the motion of air parcels at low levels as they are joining the warm conveyor belt of cyclones ([29]). This state of affairs minimises the loss of buoyancy by an air parcel as it flows over the ocean (warm air over warm water), and it favours deep saturated updrafts as the parcel's moist entropy becomes comparable to that of the environment at the tropopause.

Through this chain of events, the Gulf Stream acts in effect as a region where deep updrafts are concentrated. Because the weather systems are open systems ([10]), the compensating downward mass flux is not occuring locally over the Gulf Stream but is spread out over a great lateral extent. As a result, a "line of net upward motion" is created along the path of the Gulf Stream, with a well defined (narrow) spatial structure but a stochastic character in time: this is the $\boldsymbol{F}$ term in (2). The time mean component of the latter represents a simple squeezing of the upper levels of the troposphere and acts in effect as a line source of anticyclonic vorticity. It is suggested in Fig. 8 that this process is the reason for the robust upper level anticyclone found in studies simulating the response of the troposphere to a smoothing of the SST gradient in the North Atlantic ([20]; [27]).

5 Oceanic mesoscale and the Jet Stream

Recent modeling work has suggested that a vigourous mesoscale oceanic eddy field has the potential to shift the storm track and Jet Stream poleward. This was seen in a regional model of the North Pacific run at 27km resolution but not at a lower resolution of 162 km ([17]), in an idealised model run at 18km resolution ([6]), and in global model simulations at approximately 25 km resolution ([33]; [14]). Although this effect was only seen when the resolution of the atmospheric model was high enough, the mechanism proposed is not associated with a $\boldsymbol{F}$ term like, but consists in a more effective growth of baroclinic waves in the presence of a mesoscale oceanic eddy field, i.e. a $\boldsymbol{L}$ term in the framework of (2).

As illustrated in Fig. 9, the presence of the oceanic mesoscale eddies lead to correlations between updrafts and moisture / temperature at the top of the marine boundary layer, leaving a more favourable environment for the growth of baroclinic disturbances. Further experiments by [6], in which the

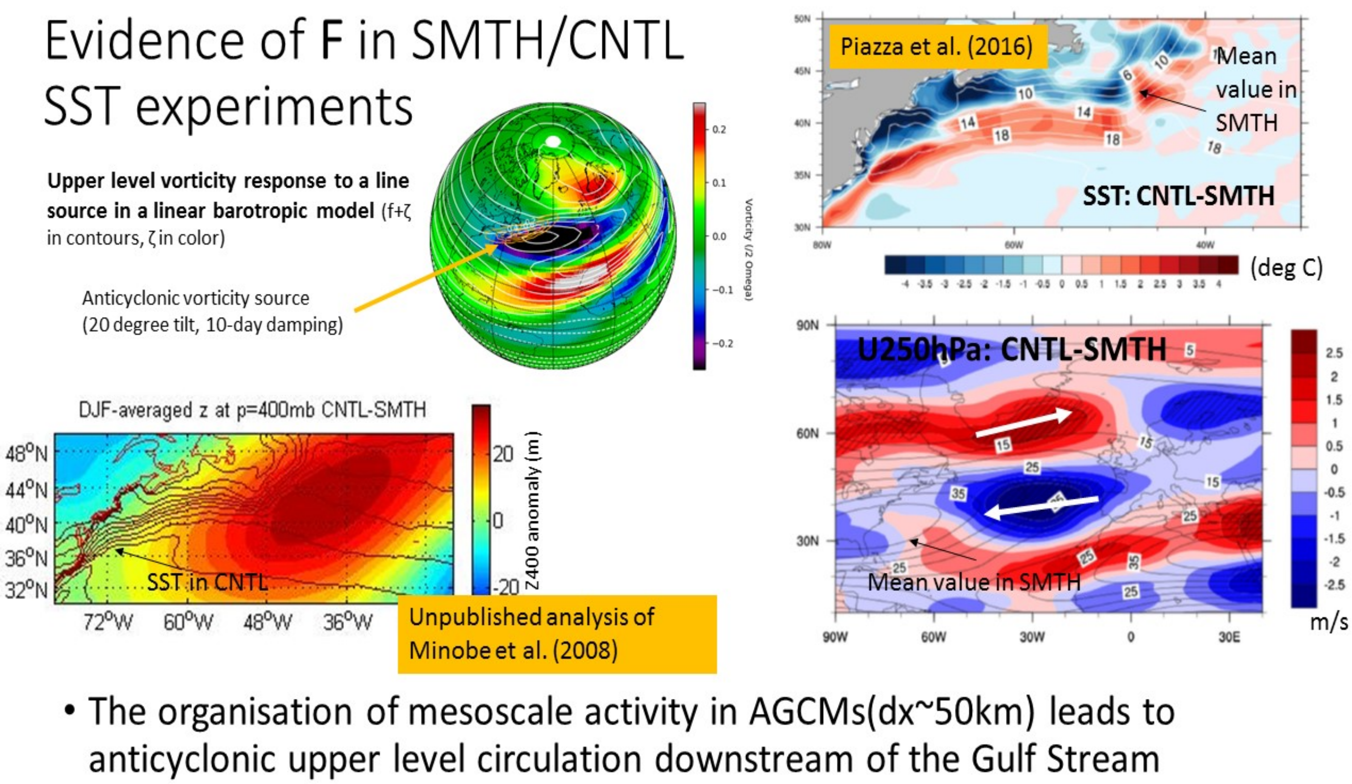

Figure 8: Vorticity forcing of upper tropospheric levels by the Gulf Stream. See text for details.

oceanic eddy field is replaced by a simple northward shift of the SST front were able to reproduce this effect, emphasizing that it is not the mesoscale eddies themselves which matter, but the generation of a warmer and moistier environment for the baroclinic waves (in this case as a result of a transverse circulation induced by the shift of the front). The mechanism seems robust and present in much simpler models ([3]). However, since it falls in the $\boldsymbol{L}$ term category, the overall response of the storm-track Jet Stream system to variability in the oceanic mesoscale eddy field will likely be sentitive to details of the experiment or the forecast being conducted (Quantum Café behaviour).

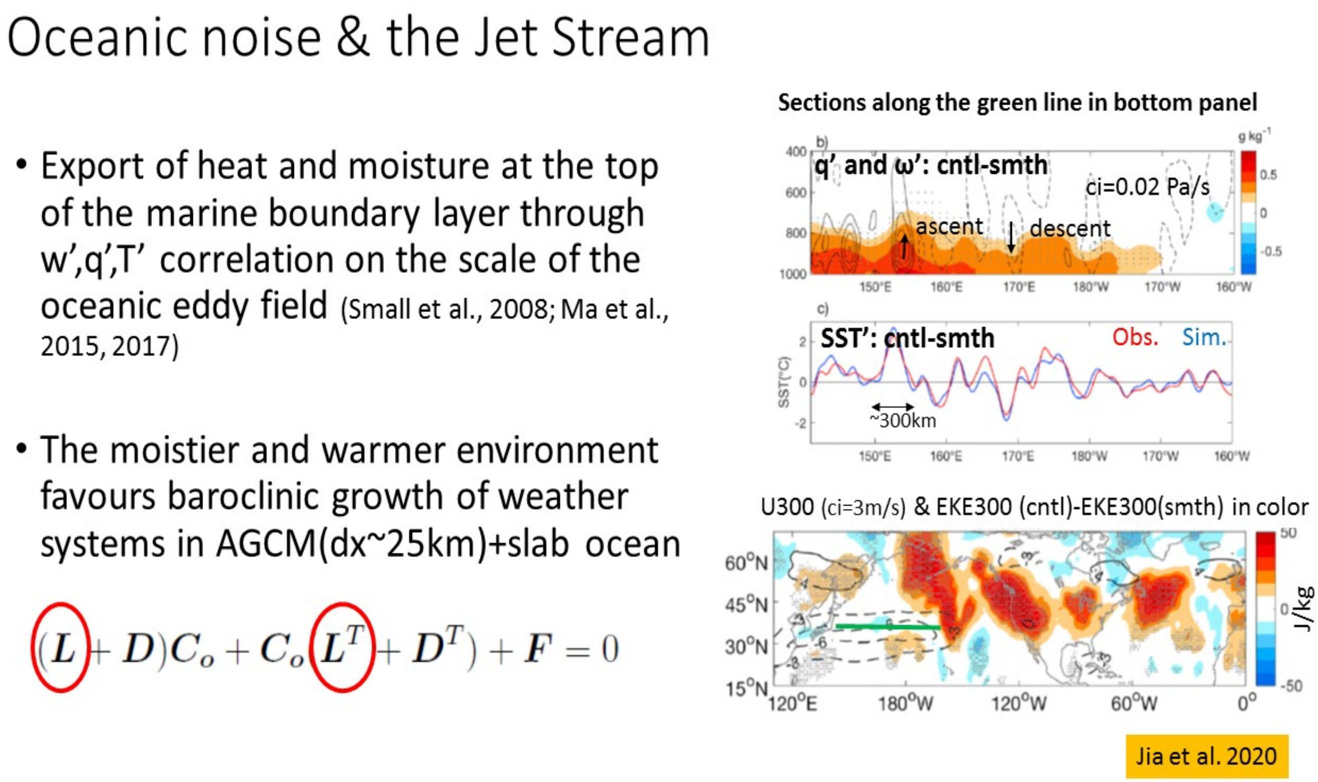

Figure 9: Impact of the oceanic mesoscale eddy field on baroclinic growth of atmospheric disturbances. See text for details.

6 The coupling of oceanic and atmospheric mesoscale

The separate discussion of the oceanic and atmospheric mesoscale variability naturally leads to wonder whether there might be a direct interaction between them. In simple theories of frontogenesis, fronts develop as singularities because no dissipative process is present ([12]). But the mere thermal interaction between air and water is naturally expected to lead to a preferred orientation and width for the atmospheric fronts, with a thermally equilibrated configuration the most likely –warm (cold) air over warm (cold) waters ([22]). Indeed, perhaps it is only a coincidence, but the atmospheric mesoscale L_a, defined as the scale where the Rossby number reaches unity, is comparable to the oceanic deformation radius L_o, which sets the width of oceanic fronts:

$$L_a = \frac{U_a}{f} \sim \frac{N_o H_o}{f} = L_o \approx 100km \tag{4}$$

An illustration of this coupling is shown in Fig. 10.

7 Conclusion

Should we be disappointed that different AGCMs forced by Gulf Stream shifts lead to different responses? Not if it turns out that, in Nature, the response of the atmosphere to changes in Gulf Stream state is controlled by the eddy mean flow feedback. If this were indeed the case, the AGCMs' behaviour would then just be the expression of a physical effect present in Nature, *namely that, when it comes to predicting the response of the storm-track / Jet Stream system to Gulf Stream changes, details will matter.*

Conversely, it could well be that in Nature the response of the atmosphere to changes in Gulf Stream state is not controlled by the eddy mean flow feedback, although it is in our AGCMs, and that this difference is leading to a serious distortion in how we simulate the impact of the ocean on the Jet Stream. We simply do not know if this is the case at present, but the application of diagnostic models such as the one summarised in eq. (2) to reanalysis data could help in answering this question.

Finally, the development of hi-res ocean models coupled to statistical atmospheric models in which the eddy mean flow sensitivity is minimised (see for example what happens with the NAO and the SST tripole) could help

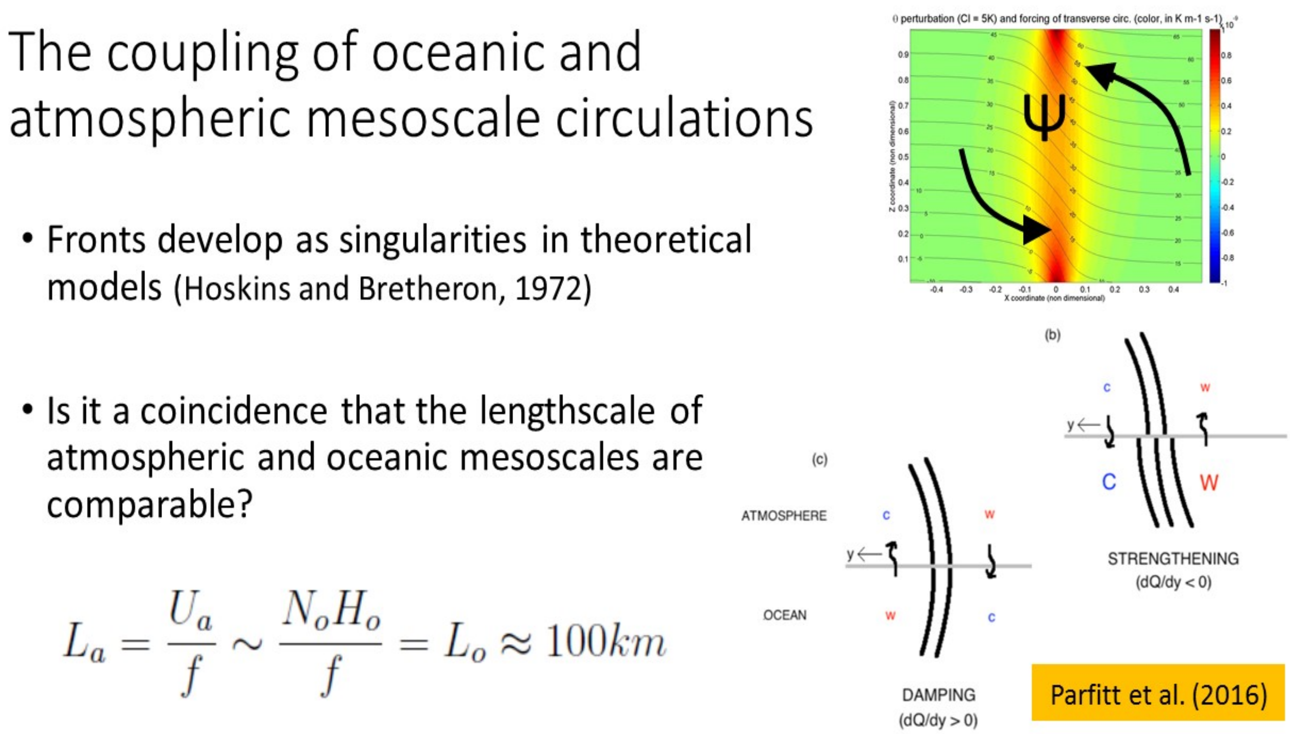

Figure 10: Thermal coupling of the oceanic and atmospheric mesoscale. See text for details.

in isolating, in fully coupled hi-res models, the contribution of the oceanic forcing occurring on scales smaller than the atmospheric deformation radius to the coupled model's variability.

8 Acknowledgements

I'm grateful for the invitation by WHOI to participate remotely to the "Whither the Gulf Stream workshop". Discussions with many at this workshop, as well as at the Storm Track workshop in Ile d'Oléron and at the National Climate Dynamics workshop held by the University of East Anglia, all occurring in June 2022 (!), helped clarify the ideas presented here.

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